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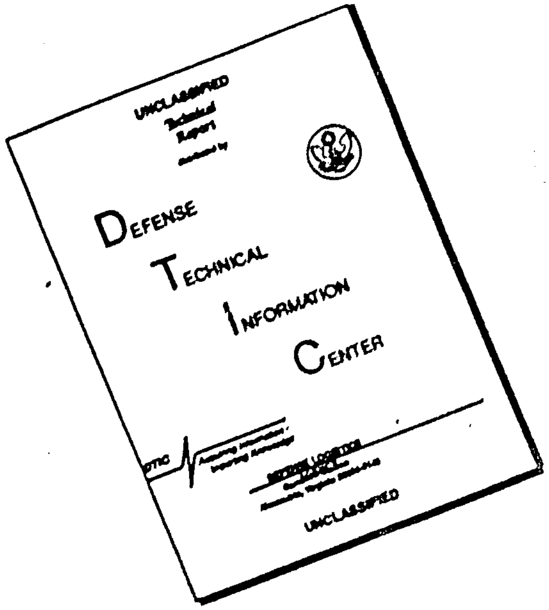

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FINAL PROGRESS REPORT

CONTRACT DA-19-059-ORD-584

RESEARCH AND DEVELOPMENT WORK
COVERING UNCONVENTIONAL AMMUNI-
TION - CALIBER .60 - FOR SHORT
AIRCRAFT MACHINE GUNS

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PROGRESS REPORT

RESEARCH AND DEVELOPMENT WORK COVERING UNCONVENTIONAL AMMUNITION - CALIBER .60 FOR SHORT AIRCRAFT MACHINE GUNS - CONTRACT DA-19-059-ORD-584

Contract: DA-19-059-ORD-584
Period: March 20, 1952 through December 10, 1953
Project: TD-584-52
Previous Reports: Monthly Progr es Reports
Prepared by: Louis G. Stier

INTRODUCTION

The subject contract was executed on March 20,1952. Its purpose was basic research and development of ammunition for a proposed short aircraft caliber .60 machine gun. This gun is novel in design. The projectiles and cases are separately loaded, the latter being fired when in a position normal to the bore axis. Hence, the propellant gases must change their direction of flow by 90° before entering the bore after leaving the chamber.

The scope of the work is set forth in the contract objectives of which there are three:

a. A basic study of the effect on ballistics of free bore, free chamber volume, and gas flow direction at the chamber end.

b. A study of the relative effect on erosion of change in direction of gas flow.

c. The development of a practical, ballistically efficient type of case closure.

In other words, the objectives of the contract are comprised under the headings Interior Ballistics, Erosion and Case Closure. The reasons behind these objectives are set forth in the following paragraphs.

An interior ballistics study is required because of some unusual features incorporated in this gun design. It is necessary, for example, to employ large free run* and free volume; that is to say, the initial resistance and loading density are lower than in conventional guns.

Also, in the new gun, the axis of the chamber volume is normal to the bore axis of the gun. The propellant gases emerging from the chamber must change their flow direction by 90°. Immediately, two questions come to mind. What is the effect on ballistics—peak pressure and muzzle velocity—of the change in gas flow direction? Also, how serious will erosion be in the right angle bore section between chamber and gun bore?

Finally, in the proposed new gun, cartridge case and projectile are separately loaded. Hence, a mouth closure must be devised for retaining the propellant in the cartridge case. This closure must be ballistically efficient. This implies: that the closure provide sufficient confinement to ensure good powder ignition; that the closure operate in such a way that good pressure and velocity regularity be obtained; that no parts of the closure emerge from the gun muzzle on firing. In addition, the closure must be a practical one from a production loading standpoint.

* The free run, or free bore, is the distance the projectile

SUMMARY AND CONCLUSIONS

1. A "dimensional analysis" of the basic interior ballistics equations has been carried out. From this analysis the groups of parameters to be used in correlating pressure and velocity data are derived.

2. Velocities and pressures obtained in a conventional gun for wide variations in the values of the loading parameters have been successfully correlated using these same parameters. The success of the correlation is measured by goodness of fit to the predicted straight line relationship.

3. The peak pressure gives the best straight line when a pressure burning index of 0.85 is used.

4. "Quickness" was varied by blending powders of different web. A method of computing the "effective-quickness" of this composite charge has been developed. The results indicate that this method is satisfactory.

5. Free bore in the gun does not affect the muzzle velocity-to-peak pressure relationship. This means that a drop in pressure - and hence a drop in muzzle velocity - due to an increase in free bore can be compensated by a change in the powder quickness.

6. Values of peak pressure do not change much with changes in free bore in the neighborhood of 2.5" or less. At a free bore of 3" there is a drop in peak pressure at low pressure levels - 20,000 to 30,000 psi. At higher pressure levels - 50,000 to 60,000 psi - the peak pressure is not affected even by a free run of 3".

7. When conventional cases are used and the bullets are not seated in the cases, neck tears and shoulder separations occur, especially at low loading densities and high pressures. Such casualties are not obtained with cases cut off at the shoulder. This indicates that the cartridge case to be used in the unconventional gun should have a straight wall with a slight taper.

8. In the unconventional test gun gas sealing is obtained between the barrel and the receiver by machining a raised boss on the barrel surface in contact with the receiver. The seal is provided by the mechanical pressure between these two steel surfaces. Even at peak gun pressures of 83,000 psi no serious gas leakage was observed.

9. The ballistic effect - change in peak pressure or muzzle velocity - resulting from a 90° change in direction of gas flow is negligible.

10. Serious erosion was obtained after firing 140 rounds in the unconventional gun in which the direction of gas flow is changed by 90°. Deep erosion grooves begin to form on the inside surface of the turn. The firing rate was very slow - about one shot every ten minutes.

11. The erosion described above did not produce a decrease in the muzzle velocity level.

12. A closure design has been worked out which is ballistically efficient and adaptable to practical production methods.

13. No closure material has been found which has adequate physical strength and at the same time burns completely in the gun.

14. Cellulose nitrate has good physical strength but only about .020" burns in the gun when large diameter closure discs are employed. A closure disc of at least .040" thickness is required in this application for adequate strength. Ballistite burns completely but is too flexible. JPN propellant sheet is borderline in both respects but may be adequate. Two other possibilities - plastic sheet impregnated with potassium perchlorate, and nitrated cloth - are possibilities for further investigation.

PATENT STATEMENT

The work reported here does not involve patent infringement and no inventions were made in the performance of the contract.

LIST OF SYMBOLS

m projectile weight

ω propellant charge weight

v velocity

v_m muzzle velocity

t time

p pressure

p_p peak pressure

p_0 resistance pressure

z fraction of powder burned

A powder quickness

α burning rate index

$\varphi(z)$ form function

f powder potential

C_o chamber volume

η powder co-volume

x projectile travel

γ ratio of specific heats

$\bar{\gamma}$ ratio of specific heats modified to take into account heat loss

F bore cross-section area

ζ generalized travel

τ generalized time

π generalized pressure

ρ generalized resistance

LIST OF SYMBOLS (cont.)

μ travel factor

ν reciprocal time factor

λ pressure factor

M general ballistic parameter

ρ_0 initial resistance at $\tau = 0$

β measure of co-volume effect

η expansion ratio

η_b expansion ratio at "burnt"

ζ function of η

Δ loading density

δ powder density: 1.6 gm/cc.

EXPERIMENTAL DETAILS

This section of the report will consist of three parts. Part I will be concerned with Interior Ballistics. After presentation of the general theory, there follows a discussion of the experimental firings which is sub-divided into section (1), Ballistics in a Standard Gun; section (2), Ballistics in a Gun with Variable Free Bore; and section (3), Ballistics in a Gun with Change in Gas Flow Direction. Part II will deal with erosion and Part III with Case Closure.

The plan used to carry out the objectives of this project was as follows. We wish to determine the effect on ballistics, if any, of change in gas flow direction, free bore, etc. This implies that ballistics in the conventional gun have been established. Hence, the first step will be to determine the peak pressure and muzzle velocity in terms of the conventional gun parameters. Next, firings will be carried out in a gun having different values of free bore. Variations of peak pressure and muzzle velocity from the values determined in step one can then be ascribed to changes in free bore. In the third and final step the same procedure will be carried through for the gun with change in gas flow direction. Thus the effect of free bore and change in gas flow direction can be determined.

Because of the nature of this study, it was possible to construct a detailed test program before any experimental work was done. This schedule will be considered in detail in conjunction with the results of the experimental firings.

I. INTERIOR BALLISTICS STUDY

A. Theory

1. Generalized Variables

The problem is to determine the effect of free chamber volume, free bore and gas flow direction on "ballistics". "Ballistics" will be taken to mean peak pressure, muzzle velocity, and ignition characteristics. The solution to the problem will be a plot of muzzle velocity vs. the gun and cartridge parameters and a plot of peak pressure vs. the same parameters. The gun and cartridge parameters include, in addition to those mentioned above, such things as powder charge weight, expansion ratio, projectile mass, etc.

Interior ballistics theories show that $\frac{1}{2}\frac{m+\omega/3}{\omega}V_m^2$, the muzzle energy per grain, should correlate with some function of P_p, Δ and γ, where m, ω, V_m, P_p, Δ, and γ, are projectile mass, powder weight, muzzle velocity, peak pressure, loading density, and expansion ratio respectively. The loading density is here defined by

$$\Delta = \frac{\omega}{C_0}$$

and the expansion ratio by

$$\gamma = \frac{C + C_0}{C_0}$$

where C_0 is the initial volume of the chamber and $C_0 + C$ is the total volume of the gun including the chamber.

Similarly, the same theory shows that the peak pressure should correlate with m, C_0, ω, A, σ, and α. Here A, σ, and α are the powder quickness, the bore cross section area, and the pressure burning index respectively.

These statements regarding the muzzle velocity and peak pressure will now be justified. This can be done by writing the equations of interior ballistics in terms of generalized or non-dimensional variables. We will consider a ballistic system with the following assumptions:

(1) A generalized rate of burning that can be represented by a function of the form, P^{α}, where P is the pressure and α is an exponent usually less than one.

(2) A form function $\varphi(z)$ which describes how the surface of the powder varies during the course of burning. This function includes a constant A which will be called the "quickness".

(3) Assumptions (1) and (2) include implicitly the assumption that the dependence of the burning rate on pressure and surface area can be written as the product of two function, $\varphi(z)\, P^{\alpha}$.

(4) A resistance $R(x)$ which is a function of travel, x, represented by a "pressure" which is the resistance force per unit area of bore cross section.

In terms of these quantities, the ballistic equations can be written as follows:

(1) The equation of motion

$$\left(m + \frac{w}{2}\right)\frac{dv}{dt} = \sigma\,(P - R) \qquad (1)$$

(2) The rate of burning equation

$$\frac{dz}{dt} = A\,\varphi(z)\,P^{\alpha} \qquad (2)$$

(3) The energy equation

$$f\omega z = P\left[C_0 + \sigma x - \frac{\omega}{\delta}(1 - z) - \ldots\right] + \cdots \qquad (3)$$

$$\cdots + \frac{1}{2}(\gamma - 1)\left(m + \frac{w}{3}\right)v^2 + (\gamma - 1)\,\sigma \int_0^x R\,dx$$

Now let

$$x = \mu\,\xi \qquad (4)$$

$$\tau = \nu\,t \qquad (5)$$

$$P = \lambda\,\Pi \qquad (6)$$

$$R = \lambda\,\rho \qquad (7)$$

In these equations ξ, τ, π, and ρ are dimensionless or generalized travel, time, pressure and resistance respectively. The fraction of powder burned, z, is already a dimensionless quantity. In terms of these new variables, equations (1), (2) and (3) can be written

$$\ddot{\xi} = \frac{\sigma\lambda}{\nu^2\mu(m+\omega/2)}(\pi-\rho) \tag{8}$$

$$\dot{z} = \left[\frac{A\varphi(z)\lambda^{\alpha}}{\nu}\right]\pi^{\alpha} \tag{9}$$

$$z = \frac{\lambda}{f\omega}\left(C_0-\frac{\omega}{\delta}\right)\left[1+\frac{\sigma\beta\xi}{C_0-\frac{\omega}{\delta}} - \frac{\eta-\frac{1}{\delta}}{\frac{1}{\Delta}-\frac{1}{\delta}}z\right]\pi + \frac{1}{2}(\gamma-1)\left(m+\frac{\omega}{3}\right)\mu^2\nu^2\dot{\xi}^2 + \dots + (\gamma-1)\sigma\mu\lambda\int_0^{\xi}\rho\,d\xi \tag{10}$$

We now give values to the arbitrary constants μ, ν, λ.

In (8) let $\frac{\sigma\lambda}{\nu^2\mu(m+\frac{\omega}{2})} = 1$; then $\nu^2 = \frac{\sigma\lambda}{\mu(m+\frac{\omega}{2})}$ (11)

In (10) let $\frac{\lambda(C_0-\omega/\delta)}{f\omega} = 1$; and $\frac{\sigma\mu}{C_0-\omega/\delta} = 1$ (12)

Then $\lambda = \frac{f\omega}{C_0-\omega/\delta}$; $\mu = \frac{C_0-\omega/\delta}{\sigma}$; and from (11)

$$\nu = \frac{\sigma}{C_0-\omega/\delta}\sqrt{\frac{f\omega}{m+\omega/2}} \tag{13}$$

Substituting these values, equations (8), (9) and (10) can be written

$$\ddot{\xi} = \pi-\rho \tag{14}$$

$$\dot{z} = \frac{\pi^{\alpha}}{\sqrt{M}} \tag{15}$$

$$z = \pi\left[1+\xi-Bz\right] + (\gamma-1)\int_0^{\xi}\rho\,d\xi + \frac{(\gamma-1)}{2}\dot{\xi}^2 \tag{16}$$

where, by definition

$$M = \left[\frac{\sigma}{A\varphi(z)}\right]^2\frac{(C_0-\omega/\delta)^{2\alpha-2}}{(m+\omega/2)(f\omega)^{2\alpha-1}} \tag{17}$$

$$B = \frac{\eta-1/\delta}{\frac{1}{\Delta}-\frac{1}{\delta}} \tag{18}$$

Also, the new "generalized variables" are defined in terms of the old variables by the following relations:

$$\xi = \frac{\sigma x}{C_0 - \omega/\delta} \tag{19}$$

$$\tau = \frac{\sigma}{C_0 - \omega/\delta} \sqrt{\frac{f\omega}{m + \omega/2}}\; t \tag{20}$$

$$\pi = \frac{P\left[C_0 - \omega/\delta\right]}{f\omega} \tag{21}$$

$$\rho = \frac{R\left[C_0 - \omega/\delta\right]}{f\omega} \tag{22}$$

The initial conditions that must be satisfied are:

$$\xi = 0, \quad \frac{d\xi}{d\tau} = 0, \quad \pi = \rho_0 \tag{23}$$

where ρ_0 is the value of ρ at $\tau = 0$.

We end up with the following list of parameters. The values assigned to these parameters determine the velocity and pressure in the solution for any particular case.

(1) β, a measure of the effect of co-volume

(2) M, sometimes called the "general ballistic parameter", a measure of the rate of burning

(3) $\bar{\gamma}$, the ratio of specific heats, modified to take into account heat loss.

(4) α, the pressure index of the propellant which depends on the composition of the propellant.

(5) ρ, the resistance function and ρ_0 its value at $\tau =$.

2. <u>Quickness Values to be Used in Case of Duplex Loads</u>

Few powders are available in the quickness range required for these tests. Hence, it was necessary to employ duplex loaded samples. A "duplex" load is one in which the charge is a composite of two or more powders having different properties.

In order to fit such data into the equations developed above, it is necessary to specify a single equivalent property of the composite charge in terms of the known properties of the individual constituents.

We will assume that there are two propellants in the composite charge, each having the same composition and, hence, the same potential and co-volume. We will assume that in the composite charge there are ω_1 grams of propellant having quickness A_1 and ω_2 grams having quickness A_2. If the composite charge were to be replaced by a single charge of $\omega = \omega_1 + \omega_2$ grams, what must be the quickness, A, of the single charge?

Strictly speaking, it is not possible to find a single charge of quickness A which will give the same ballistic results as a composite charge like the one described above if constant burning surface is assumed. In the case of the composite charge, for example, the slower constituent determines the time to the end of burning. If the equivalent single charge is to have the same time to end of burning, then it too must have the same quickness as that of the slower constituent. Hence, under these conditions, an equivalent charge of this type does not exist. If constant burning surface is not assumed, the problem is soluble. In effect, a composite charge of two constant burning surface powders having different quicknesses is equivalent to a single charge having a burning surface which is not constant but varies with the burning.

To a first approximation, it is possible to define an equivalent powder quickness for a composite charge. We simply require the rate of gas generation to be the same for the equivalent single charge as for the composite charge.

Assume a law of burning given by

$$\omega \frac{dz}{dt} = \omega A P^{\alpha} \tag{24}$$

Then, in the composite load, the rate of gas generation by the first constituent having a weight of ω_1 grams is

$$\omega_1 \frac{dz_1}{dt} = \omega_1 A P^{\alpha} \tag{25}$$

And the rate of gas generation of the second constituent having a weight of ω_2 grams is

$$\omega_2 \frac{dz_2}{dt} = \omega_2 A_2 P^{\alpha} \tag{26}$$

Hence, the total rate of gas generation of the composite load is

$$\omega_1 \frac{dz_1}{dt} + \omega_2 \frac{dz_2}{dt} = \omega_1 A_1 P^{\alpha} + \omega_2 A_2 P^{\alpha} \tag{27}$$

The equivalent single load must have a charge weight of $\omega = \omega_1 + \omega_2$ grams. Let the quickness of the equivalent load be A. Then

$$\omega A P^{\alpha} = \omega_1 A_1 P^{\alpha} + \omega_2 A_2 P^{\alpha} \tag{28}$$

or

$$A = \frac{\omega_1 A_1 + \omega_2 A_2}{\omega_1 + \omega_2} \tag{29}$$

3. Velocity Correlation

We return to the equations on page 10. The problem is to determine the variables to use in making a velocity plot. It is not possible to keep all the parameters in the problem and get all the data in one plot. Simplifications have to be made. Hence, we will first assume that the resistance is a second order factor; also, the co-volume term. Both these terms will be neglected. These assumptions are probably pretty accurate as far as the velocity plot is concerned since the parameters in question affect mainly the peak pressure. But as will be seen in what follows, the velocity will be plotted in terms of the peak pressure and, hence, these factors will be included indirectly.

The equations on page 10 can then be written:

$$\ddot{\xi} = \pi \tag{30}$$

$$\dot{z} = \frac{\pi^{\alpha}}{\sqrt{M}} \tag{31}$$

$$z = \pi\left[1+\xi\right] + \frac{(\gamma-1)}{2}\dot{\xi}^{2} \tag{32}$$

Now let

$$\pi = \pi' M^{-\frac{1}{3-2\alpha}} \tag{33}$$

$$z = z' M^{-\frac{1}{3-2\alpha}} \tag{34}$$

$$\tau = \tau' M^{-\frac{1}{4\alpha-6}} \tag{35}$$

Then (30), (31) and (32) become

$$\frac{d^{2}\xi}{d\tau'^{2}} = \pi' \tag{37}$$

$$\frac{dz'}{d\tau'} = \pi'^{\alpha}$$

$$z' = \pi'\left[1+\xi\right] + \frac{(\gamma-1)}{2}\left(\frac{d\xi}{d\tau'}\right)^{2} \tag{38}$$

The solution of these equations depends on only three parameters: α, γ, and π_0'. Conditions at "burnt" - the time when all the powder is burned - depend also on M since

$$z = z' M^{-\frac{1}{3-2\alpha}} \tag{39}$$

and when $z = 1$ (that is "burnt")

$$z' = M^{\frac{1}{3-2\alpha}} \tag{40}$$

If α , $\bar{\gamma}$ are given to be the same for all samples tested, then the solutions will depend only on π_0' and M .

Now these equations are not to be solved analytically. Hence, the values of quantities at "burnt" will not be known. As will be seen later, these values are required for the velocity plot. Hence, for the velocity plot only, the pressure index will be assumed equal to 1 , $\alpha = 1$, that is, linear rate of burning. As was cited above, the muzzle energy is not sensitive to the law of burning assumed. This law of burning will affect principally the peak pressure and this is indirectly taken into account since the pressure is one of the parameters in the velocity plot. Hence (36), (37) and (38) can be written

$$\frac{d^2\xi}{d\tau'^2} = \pi' \qquad (41)$$

$$\frac{d\tau'}{d\tau} = \pi' \qquad (42)$$

$$z' = \pi'\left[1+\xi\right] + \frac{\bar{\gamma}-1}{2}\left(\frac{d\xi}{d\tau}\right)^2 \qquad (43)$$

The muzzle energy is equal to the kinetic energy of the projectile up to the position at which all the powder is burned plus the work done by the powder gases from that point to the muzzle:

$$\frac{1}{2}\left(m+\frac{w}{3}\right)V_m^2 = \frac{1}{2}\left(m+\frac{w}{3}\right)V_b^2 + \sigma\int_{x_b}^{x_m} P\,dx \qquad (44)$$

Let the subscript b represent the value of a quantity at "burnt"- that is, when all the powder is burned. After "burnt", we will assume adiabatic expansion to the muzzle so that

$$\sigma\int_{x_b}^{x_m} P\,dx = \frac{\sigma P_b}{\bar{\gamma}-1}\left[x_b + \frac{C_0 - \frac{w}{\delta}}{\sigma}\right]\left[1 - \eta_0^{\bar{\gamma}-1}\right] \qquad (45)$$

where y_b is an "expansion ratio" at "burnt" defined by

$$y_b = \frac{x_m + \frac{c_0 - \frac{w}{\delta}}{\sigma}}{x_b + \frac{c_0 - w/\delta}{\sigma}}$$

Hence, the muzzle energy is given by

$$\frac{1}{2}\left(m+\frac{w}{3}\right)V_m^2 = \frac{1}{2}\left(m+\frac{w}{3}\right)V_b^2 + \frac{\sigma P_b}{\bar{\gamma}-1}\left[x_b + \frac{c_0 - \frac{w}{\delta}}{\sigma}\right]\left[1 - y_b^{1-\bar{\gamma}}\right] \quad (46)$$

Now, by (41) and (42)

$$\frac{d\xi}{d\tau'} = \eta' \quad (47)$$

and at "burnt"

$$\eta' = M \quad (48)$$

so that

$$\left(\frac{d\xi}{d\tau'}\right)_b = M \quad (49)$$

and

$$\left(\frac{d\xi}{d\tau'}\right)_b^2 = M^2 \quad (50)$$

From (35) on page 14 and (20) on page 11 with $\alpha = 1$

$$\left(\frac{m + w/3}{f w}\right) v^2 = \frac{1}{M}\left(\frac{d\xi}{d\tau}\right)^2 = \frac{1}{M}\left(\frac{d\xi}{d\tau'}\right)^2$$

Substituting in (49)

$$\left(\frac{m + w/3}{f w}\right) V_b^2 = M \quad (51)$$

Now, from (33) on page with $\alpha = 1$

$$\Pi = \frac{\Pi'}{M} \quad ; \quad M = \frac{\Pi'}{\Pi} \quad (52)$$

In particular,

$$M = \frac{\Pi_p'}{\Pi_p} \quad (53)$$

where the subscript p refers to quantities at peak pressure.

Substituting in (50)

$$\left(\frac{m + w/3}{f w}\right) V_b^2 = \frac{\Pi_p'}{\Pi_p} \quad (54)$$

Here Π_p' is a function of $\bar{\gamma}$ only. If $\bar{\gamma}$ is considered the same for all samples, Π_p' will be a constant. Π_p is defined by (20) on page 11. Substituting

$$\left(\frac{m + w/3}{f w}\right) V_b^2 = \frac{\Pi' \Delta}{P_p\left(1 - \frac{\Delta}{\delta}\right)} \quad (55)$$

Hence, the muzzle energy by equation (45) is given by the expression

$$\left(\frac{m+w/3}{f\omega}\right)V_m^2 = \frac{\pi'\Delta}{P_p\left(1-\frac{\Delta}{\delta}\right)} + \frac{2\sigma P_b}{\bar{\gamma}-1}\left[x_b + \frac{C_o - w/\delta}{\sigma}\right]\left[1-y_b^{1-\bar{\gamma}'}\right] \quad (56)$$

which can be written

$$\frac{P_p}{\Delta}\left(1-\frac{\Delta}{\delta}\right)\left(\frac{m+w/3}{f\omega}\right)V_m^2 = 2\,\frac{P_p\left(1-\frac{\Delta}{\delta}\right)}{\Delta}\,\frac{\sigma P_b}{\bar{\gamma}-1}\left[x_b + \frac{C_o - w/\delta}{\sigma}\right]\left[1-y^{1-\bar{\gamma}'}\right] + \pi' \quad (57)$$

One more simplification can be made in (56).

By equation (32) on page 14

$$z = \pi\left[1+\xi\right] + \frac{\bar{\gamma}'-1}{2}\left(\frac{d\xi}{d\tau}\right)^2$$

which in terms of the original variables is

$$f\omega z = P\left[\sigma X + C_o - w/\delta\right] + \frac{1}{2}(\bar{\gamma}-1)\left(m+\frac{w}{3}\right)V^2 \quad (58)$$

At "burnt" $z=1$ so that

$$f\omega = P_b\left[\sigma x_b + C_o - w/\delta\right] = \frac{1}{2}\left[\bar{\gamma}-1\right]\left[m+\frac{w}{3}\right]V_b^2 \quad (59)$$

By (55)

$$\left(\frac{m+w/3}{f\omega}\right)V_b^2 = \frac{\pi'\Delta}{P_p\left(1-\frac{\Delta}{\delta}\right)}$$

Substituting in (59)

$$1 - \frac{P_b}{f\omega}\left[\sigma x_b + C_o - w/\delta\right] = \frac{1}{2}\,\frac{(\bar{\gamma}-1)\pi'\Delta}{P_b\left(1-\frac{\Delta}{\delta}\right)}$$

or

$$1 - \frac{1}{2}\,\frac{(\bar{\gamma}-1)\pi'\Delta}{P_b\left(1-\frac{\Delta}{\delta}\right)} = \frac{P_p}{f\omega}\left[\sigma x_b + C_o - w/\delta\right]$$

Substituting in (56)

$$\left(\frac{m+w/3}{f\omega}\right)V_m^2 = \frac{\pi'\Delta}{P_p\left(1-\frac{\Delta}{\delta}\right)} + \frac{2}{\bar{\gamma}-1}\left[1-y_b^{1-\bar{\gamma}'}\right]\left[1-\frac{1}{2}\,\frac{(\bar{\gamma}-1)\pi'\Delta}{P_p\left(1-\frac{\Delta}{\delta}\right)}\right]$$

Let

$$\frac{2}{\bar{\gamma}-1}\left[1-y_b^{1-\bar{\gamma}}\right] = Y$$

Then (60) may be written

$$\left(\frac{m+\omega/3}{f\omega}\right) V_m^2 = \frac{\pi'\Delta}{P_p\left(1-\frac{\Delta}{\delta}\right)} + \bar{Y} - \frac{1}{2}\,\frac{(\bar{\gamma}-1)\,\pi'\Delta\,\bar{Y}}{P_p\left(1-\frac{\Delta}{\delta}\right)}$$

Multiply through by $P_p\left(1-\frac{\Delta}{\delta}\right)$ and we obtain

$$\frac{P_p\left(1-\frac{\Delta}{\delta}\right)}{\Delta}\left(\frac{m+\omega/3}{f\omega}\right) V_m^2 = \frac{P_p\left(1-\frac{\Delta}{\delta}\right)}{\Delta}\,\bar{Y} + \pi'\left[1-\frac{1}{2}(\bar{\gamma}-1)\,\bar{Y}\right]$$

In this equation, the term $\bar{Y}$ is determined by barrel cut-off tests, but in terms of the expansion ratio

$$\gamma'_m = \frac{c_0+\sigma x_m}{c_0} \qquad \text{rather than}$$

$$\gamma_b = \frac{\sigma x_m + c_0 - \omega/\delta}{\sigma x_b + c_0 - \omega/\delta}$$

Since this correction is a second-order one, and since in any case the function is determined empirically, this can be done without introducing appreciable error.

A plot then of $\frac{P_p(1-\Delta/\delta)}{\Delta}\left(\frac{m+\omega/3}{f\omega}\right)V_m^2$ vs. $\frac{P_p(1-\Delta/\delta)}{\Delta}$ should give a straight line with slope $\bar{Y}$ - if $\bar{Y}$ is normalized to the same expansion ratio for all samples - and intercept $\pi'\left[1-\frac{1}{2}(\bar{\gamma}-1)\bar{Y}\right]$.

4. Pressure Correlation

We return once more to the equations on page 14. If resistance, co-volume, and the form function of the propellant are neglected, we find that the generalized pressure is given by (33):

$$\pi = \pi' M^{-\frac{1}{3-2\alpha}}$$

By (21) on page 11

$$\pi = \frac{F\left(c_0-\omega/\delta\right)}{f\omega}$$

$$F = \frac{f\omega}{c_0-\omega/\delta}\, M^{-\frac{1}{3-2\alpha}}\,\pi' \qquad (62)$$

where the factor π' is some function of α and $\bar{\delta}$. We will assume the same values of α and $\bar{\delta}$ for all cases. This implies that the heat loss does not change from sample to sample. Although this is not strictly true, small differences in heat loss will not have much effect on the peak pressure. The heat loss will show up most strongly on the muzzle velocity. Hence, π_p' will be constant for all samples and the peak pressure will be given by

$$P_p = \frac{f\Delta}{1 - \Delta/\delta} M^{-\frac{1}{3-2\alpha}} \pi_p' \qquad (63)$$

If, when $\frac{P(1 - \Delta/\delta)}{\Delta}$ is plotted against $M^{-\frac{1}{3-2\alpha}}$, a straight line is not obtained, the deviations from the straight line can be ascribed to neglect of the factors, resistance, co-volume, powder form function, etc.

What has been said above assumes that the peak pressure occurs before all the powder is burned. Otherwise, peak pressure will occur at "burnt" and will be given by

$$P_p = P_b = \frac{f\Delta}{1 - \Delta/\delta} M^{-\frac{1}{3-2\alpha}} \pi_b' \qquad (64)$$

and π_b' is itself a function of M. In this study, peak pressure will occur before "burnt" in all cases so that (63) will hold.

5. Conclusions

To sum up: the above analysis points out the significant relationships for peak pressure and muzzle velocity correlation with the interior ballistic variables. These are:

(1) For muzzle velocity:

$$\frac{P_p(1-\Delta/\delta)}{\Delta}\,\frac{m+w/3}{w}\,V_m^2 \sim \frac{P_p(1-\Delta/\delta)}{\Delta}\,\bar{Y} + \pi'\left[1-\gamma(\gamma-1)\bar{Y}\right] \qquad (65)$$

where $\bar{Y}$ is determined empirically, and

(2) For peak pressure

$$P_p \sim \frac{\Delta}{1-\Delta/\delta}\,M^{-\frac{1}{3-2\alpha}}\,\pi_1' \qquad (66)$$

where π_1' is considered constant and

$$M \sim \left[\frac{\sigma}{A}\right]^2 \frac{(C_0 - w/\delta)^{2\alpha-2}}{(m+w/2)\,w^{2\alpha-1}}$$

These relationships are derived on the basis of the following assumptions:

(1) neglect of co-volume

(2) neglect of resistance

(3) constant of α, f and γ; hence, also constant heat loss

(4) constant burning surface, $\varphi(z) = 1$

It follows that deviations of firing results from the plots of these relationships can be ascribed to cases where the above assumptions are not justified. Hence, it is to be expected, for example, that samples having low loading density or large free run (low initial resistance) will show large deviations.

B. Experimental Results

The experimental part of the program comprised three phases in each of which a different type of gun was used.

1. Basic Interior Ballistics Relations in Conventional Gun

In this part of the program a standard straight-bore caliber .60 gun was used. The free bore and the chamber volume were maintained constant. The loading density was varied by changing the powder charge. In determining what parameters had to be varied, we were guided by the correlation equations (65) and (66) given above. The range of variation of these parameters was determined from the probable range expected in the unconventional gun, and was as follows:

W : 850, 1200 and 1425 grains

ω : 358 to 610 grains

Δ : .553 to .942

A : from .498 to 1.896. Standard caliber .60 powder has an arbitrary quickness of 1.000 on this scale

Subsequently, it will be observed that in these tests the peak pressure varied from 19,480 to 63,180 psi. and that the muzzle velocity varied from 1955 to 3835 fps. After the above tests were completed, the effect of change in expansion ratio was determined by successive barrel cut-off.

The tests under this part of the program comprise the first thirteen items in Table I on the following page. In tests 1 to 9 inclusive, the caliber .60 bullet #60T32 was used. This bullet has a weight of 1200 grains. Powder quickness was varied by blending IMR4996, the standard caliber .60 propellant, with IMR4350, the propellant used in certain commercial sporting rifle cartridges. Various proportions of these powders were blended to give a range of quicknesses. In this way a range of peak pressures for a given loading density was obtained. To obtain low peak pressures at standard loading density, a very slow powder, FX6545, had to be used.

TABLE I

SUMMARY TABLE OF PRESSURE AND VELOCITY RESULTS ON VARIOUS CALIBER .30 LOADS

Sample	ω	m	$m+\frac{\omega}{3}$	Δ	y	F	ϑ	P_p	V_m	$\frac{1}{2}\frac{m+\frac{\omega}{3}}{\omega}V_m^2$	NORMAL $\frac{1}{2}\frac{m+\omega/3}{\omega}V_m^2$	$\frac{P_p}{\Delta}(1-\frac{\delta}{\Delta})$	Normal $\frac{1}{2}\frac{m+\frac{\omega}{3}}{\omega}V_m^2 \times \frac{\Delta}{P_p(1-\frac{\delta}{\Delta})}$
1	61[illegible]	1200	1394	.942	7.20	Normal	0"	603	3630	15.13 ×10⁶	15.13 ×10⁶	2.63 ×10⁴	39. ×10²
[illegible]	[illegible]	1200	1367	.724	7.20	Normal	0"	514	3293	14.40	14.40	3.47	47.1
3	[illegible]	1200	1394	.942	7.20	Normal	0"	195	1955	4.37	4.37	.55	37.1
[illegible]	[illegible]	1200	1341	.674	7.20	Normal	0"	501	3215	15.07	15.07	4.22	79.3
[illegible]	[illegible]	1200	1341	.674	7.20	Normal	0"	300	2912	13.02	13.02	3.27	42.5
[illegible]	[illegible]	1200	1356	.746	7.20	Normal	0"	341	2945	12.16	12.16	2.44	29.7
[illegible]	[illegible]	1200	1331	[illegible]	7.20	Normal	0"	632	3201	16.78	16.78	6.12	102.6
[illegible]	[illegible]	1200	1316	.593	7.20	Normal	0"	301	2765	14.04	14.04	4.51	63.2
[illegible]	[illegible]	[illegible]	1346	[illegible]	7.20	Normal	0"	274	2515	9.38	9.38	2.20	20.7
[illegible]	[illegible]	[illegible]	1042	[illegible]	7.20	Normal	0"	474	3035	12.56	12.56	2.07	[illegible]
[illegible]	[illegible]	[illegible]	1019	[illegible]	7.20	Normal	0"	315	3300	10.48	10.48	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1596	[illegible]	7.20	Normal	0"	474	[illegible]	14.12	14.12	[illegible]	[illegible]
13	[illegible]	[illegible]	1572	.700	7.20	Normal	0"	330	2743	13.03	13.03	[illegible]	36.7
[illegible]	[illegible]	1200	1403	.942	7.20	Normal	0"	506	3633	15.13	15.13	[illegible]	38.6
[illegible]	[illegible]	1200	1351	.700	7.20	Normal	0"	500	3180	15.03	15.03	2.90	38.6
[illegible]	[illegible]	1200	1403	[illegible]	5.88	Normal	0"	522	3511	14.12	15.03	4.09	61.5
[illegible]	[illegible]	1200	1351	.700	5.88	Normal	0"	500	3060	13.92	15.13	2.50	39.1
[illegible]	[illegible]	1200	1403	.942	5.22	Normal	0"	526	3402	13.25	15.03	4.03	60.6
[illegible]	[illegible]	1200	1351	.700	5.22	Normal	0"	506	[illegible]	13.00	15.13	[illegible]	39.4
[illegible]	[illegible]	1200	1437	[illegible]	5.22	1.450	0"	724	[illegible]	14.87	15.03	[illegible]	[illegible]
[illegible]	[illegible]	1200	1407	[illegible]	5.22	1.450	0"	663	3373	14.46	16.14	3.06	[illegible]
[illegible]	[illegible]	1200	1376	[illegible]	5.82	1.450	0"	[illegible]	3431	15.29	15.70	4.45	[illegible]
[illegible]	[illegible]	1200	1420	[illegible]	6.20	2.197	0"	594	3731	14.95	16.59	7.70	127.7
[illegible]	[illegible]	1200	1392	[illegible]	6.28	2.197	0"	435	3366	13.67	15.32	[illegible]	76.4
[illegible]	[illegible]	1200	1364	[illegible]	6.28	2.197	0"	[illegible]	3271	14.83	14.00	4.59	64.2
[illegible]	[illegible]	1200	1403	[illegible]	7.20	2.944	0"	831	3771	16.35	15.19	[illegible]	107.6
[illegible]	[illegible]	[illegible]	1377	[illegible]	7.20	2.944	0"	522	3345	14.48	16.35	3.60	59.2
[illegible]	[illegible]	[illegible]	1351	[illegible]	7.20	2.944	0"	536	3390	17.10	14.48	3.11	45.1
[illegible]	[illegible]	[illegible]	1437	[illegible]	5.22	1.450	0"	310	2999	9.09	17.10	6.71	114.7
[illegible]	[illegible]	1200	1376	[illegible]	5.22	1.450	0"	555	3230	13.55	9.86	1.61	15.9
											14.70	4.95	72.[illegible]

TABLE I (cont.)

[illegible]	ω	m	$m+\frac{\omega}{3}$	Δ	y	F	ϑ	P_p	V_m	$\frac{1}{2}\frac{m+\frac{\omega}{3}}{\omega}V_m^2$	NORMAL $\frac{1}{2}\frac{m+\frac{\omega}{3}}{\omega}V_m^2$	$\frac{P_p(1-\frac{\Delta}{\delta})}{\Delta}$	NORMAL $\frac{1}{2}\frac{m+\frac{\omega}{3}}{\omega}V_m^2 \times \frac{P_p(1-\frac{\Delta}{\delta})}{\Delta}$
31	[illegible]	[illegible]	[illegible]	[illegible]	6.2[illegible]	2.197	0"	315	2834	[illegible].63 x10^6	[illegible] x10^6	1.59 x10^4	14.07 x10^{10}
32	[illegible]	[illegible]	[illegible]	.65[illegible]	6.28	2.197	0"	480	3101	13.32	13.65	4.28	[illegible].4
33	[illegible]	[illegible]	[illegible]03	.94[illegible]	7.20	2.944	0"	222	2516	7.28	7.28	.97	7.03
[illegible]	[illegible]	1200	13[illegible]	[illegible]01	7.20	2.944	0"	455	3082	14.13	14.13	3.35	51.7
[illegible]	[illegible]	[illegible]	[illegible]03	.772	5.82	1.450	0"	33[illegible]	3360	10.[illegible]3	11.75	1.35	19.4
[illegible]	[illegible]3	700	[illegible]77	[illegible]	7.20	2.944	0"	207	3161	[illegible].24	[illegible]	1.39	11.46
[illegible]	[illegible]1	[illegible]	1632	.772	5.82	1.450	0"	700	3436	15.50	16.[illegible]2	4.[illegible]	7[illegible]
[illegible]	[illegible]3	[illegible]	1602	[illegible]	7.20	2.944	0"	412	2963	13.42	13.42	2.46	33.3
[illegible]	3[illegible]	1200	132[illegible]	.476	5.88	0	90°	43[illegible]	2932	14.[illegible]6	16.15	6.47	104.[illegible]
[illegible]	[illegible]	[illegible]	1366	.[illegible]1	5.88	0	90°	506	3104	13.[illegible]	14.9[illegible]	5.04	75.6
[illegible]	4[illegible]	[illegible]	136[illegible]	.603	5.88	0	90°	[illegible]33	3270	15.[illegible]	17.13	[illegible].62	14[illegible].3
[illegible]	[illegible]	[illegible]	1367	.61[illegible]	[illegible]	[illegible]	90°	345	3011	[illegible].40	13.44	3.42	4[illegible]
[illegible]	[illegible]	1200	14[illegible]	.[illegible]00	[illegible]	0	90°	[illegible]20	3464	13.13	14.14	3.77	56.5
[illegible]	[illegible]	[illegible]	1433	.[illegible]	5.[illegible]	[illegible]	90°	33[illegible]	2934	[illegible]	9.47	1.79	16.[illegible]

ω Powder charge in grains

m Bullet weight in grains

m' Effective projectile weight in grains ($m+\omega/3$)

Δ Loading density gm/cc

y Expansion ratio - ratio of total gun volume to chamber volume

F Free run of projectile in inches

ϑ Angle between chamber axis and bore axis

P_p Average peak pressure (10 rounds)

V_m Average muzzle velocity (10 rounds)

δ Propellant density 1.6 gm/cc

In samples 10 and 11, 850 grain bullets were employed. These were obtained by turning down #60T32 bullets to give the 850 grain weight. The nose of the bullet so obtained is a right cone with an apex angle approximately the same as the #60T32 bullet.

In samples 12 and 13, #60T33 bullets were used. These bullets were found to have a weight of 1425 grains.

a. Velocity Measurement

Lumiline disjunctors and Potter 1.6 megacycle counter chronographs were used to obtain the velocities. The disjunctors were placed at 28 and 78 feet respectively from the muzzle. A third disjunctor was positioned 53 feet from the muzzle when it was necessary to obtain ballistic coefficients on the projectiles employed in these tests. Two time records were taken on each round, the one time representing the interval between the 28 and 53 ft. disjunctors, the other that between the 53 and 78 ft. disjunctors. Using these data, it was possible to correct the observed velocities to obtain the true muzzle velocity. The thirteen samples covered a velocity range from 1955 to 3835 fps.

b. Pressure Measurement

Frankford Arsenal piezo gage #153 having a constant of 525 pounds per 100 microcoulombs was used to obtain pressure-time curves. The curves were recorded on 35mm film using a Dumont #247 oscilloscope. Standard capacities of 0.10 mfd. or 0.13 mfd. were used depending on the amplitude of the curve, The thirteen samples covered a pressure range from 19480 to 63180 psi.

c. Effect of Variation in Expansion Ratio

Barrel cut-off tests were run in order to determine the effect of change in expansion ratio on the velocity curves. Six tests were fired in all. They are represented by items 14, 15, 16, 17, 18, and 19 in Table I following page 21. The shells used in these tests were those cut off at the shoulder (see drawing SKRL-12-1652-6 following page 30).* In tests 14, 16 and 18, a load of 610 grains of IMR 4996 Lot 6432 was used; in tests 15, 17 and 19 a duplex loading of 270 grains of IMR 4996 Lot 6432 and 183 grains of IMR 4350.

Tests 14 and 15 were fired in a barrel with normal caliber .60 chamber and bore length. These tests served as control. In tests 16 and 17 one foot was cut off the muzzle of the barrel; in tests 18 and 19 an additional 6 inches.

In Table I, items 14-19, the relevant data are listed for these tests. It can be seen that efficiency (muzzle energy per grain) decreases with decreasing expansion ratio as expected. Also it should be noted that the relative decrease in efficiency is greater with the higher loading density samples #14 and #16.

The curves of figure 1 on the following page represent a plot of these data. In these curves muzzle energy per grain vs. loading density is plotted for different expansion ratios. It is apparent that muzzle energy per grain is not very sensitive to changes in loading density for a given expansion ratio.

* The reasons for the adoption of this case design are given on page 27.

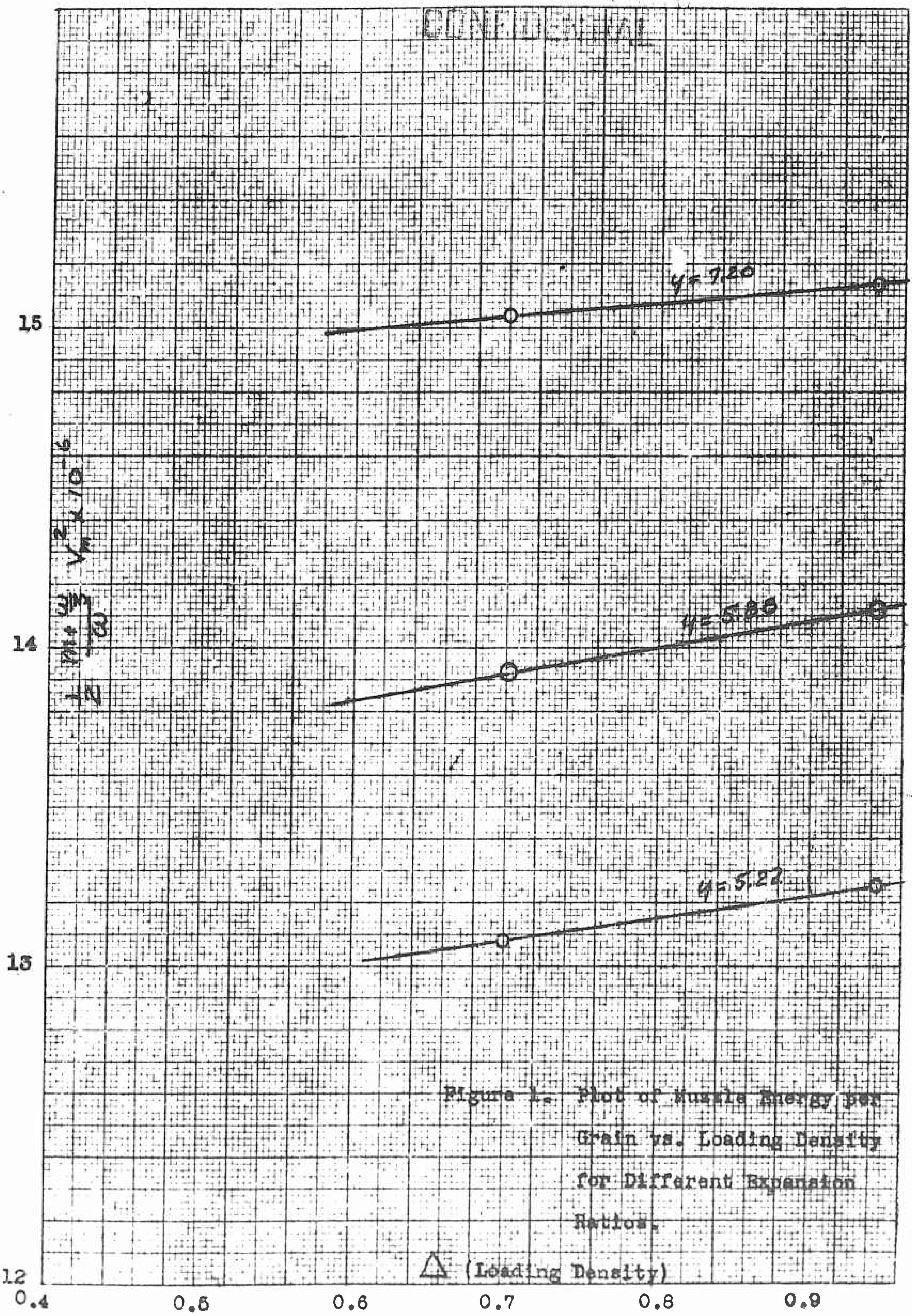

Figure 1. Plot of Muzzle Energy per Grain vs. Loading Density for Different Expansion Ratios.

These curves can be used to normalize velocity results obtained at two or more different expansion ratios to a standard expansion ratio. Corrections for expansion ratios of intermediate value can be obtained by linear interpolation.

d. Results

In Table I following page 21, pressure, velocity, and loading data are listed for all samples fired in the regular gun. Also the generalized pressure $P_r\left(\frac{1-\Delta/\delta}{\Delta}\right)$ muzzle energy per grain, etc. In figure 2 following this page $\frac{1}{2}\frac{m+\omega/3}{\omega}V_m^2 / P_r\left(\frac{1-\Delta/\delta}{\Delta}\right)$ vs. $P_r\left(\frac{1-\Delta/\delta}{\Delta}\right)$ is plotted according to the scheme of equation 65 at top of page 20, for the data obtained in the regular gun. A straight line is obtained.

Similarly in figure 3 following figure 2 the generalized peak pressure $P_r\left(\frac{1-\Delta/\delta}{\Delta}\right)$ is plotted against $\frac{1}{M}$ according to the scheme of equation 66 on page 20 . The powder quickness A which enters into the calculation of M was determined by means of equation 29 on page 13. In this equation A_1, A_2, etc. are taken proportional to the powder web, the constant of proportionality being assigned by arbitrarily chosing A for 4996 powder equal to one. The webs and arbitrary quickness numbers for the propellants used in this and subsequent tests are as follows:

Propellant	Web	Quickness Number - A
EX6544	0.0436"	0.684
EX6545	0.0598"	0.498
IMR4996	0.0298"	1.000
IMR4350	0.0157"	1.896

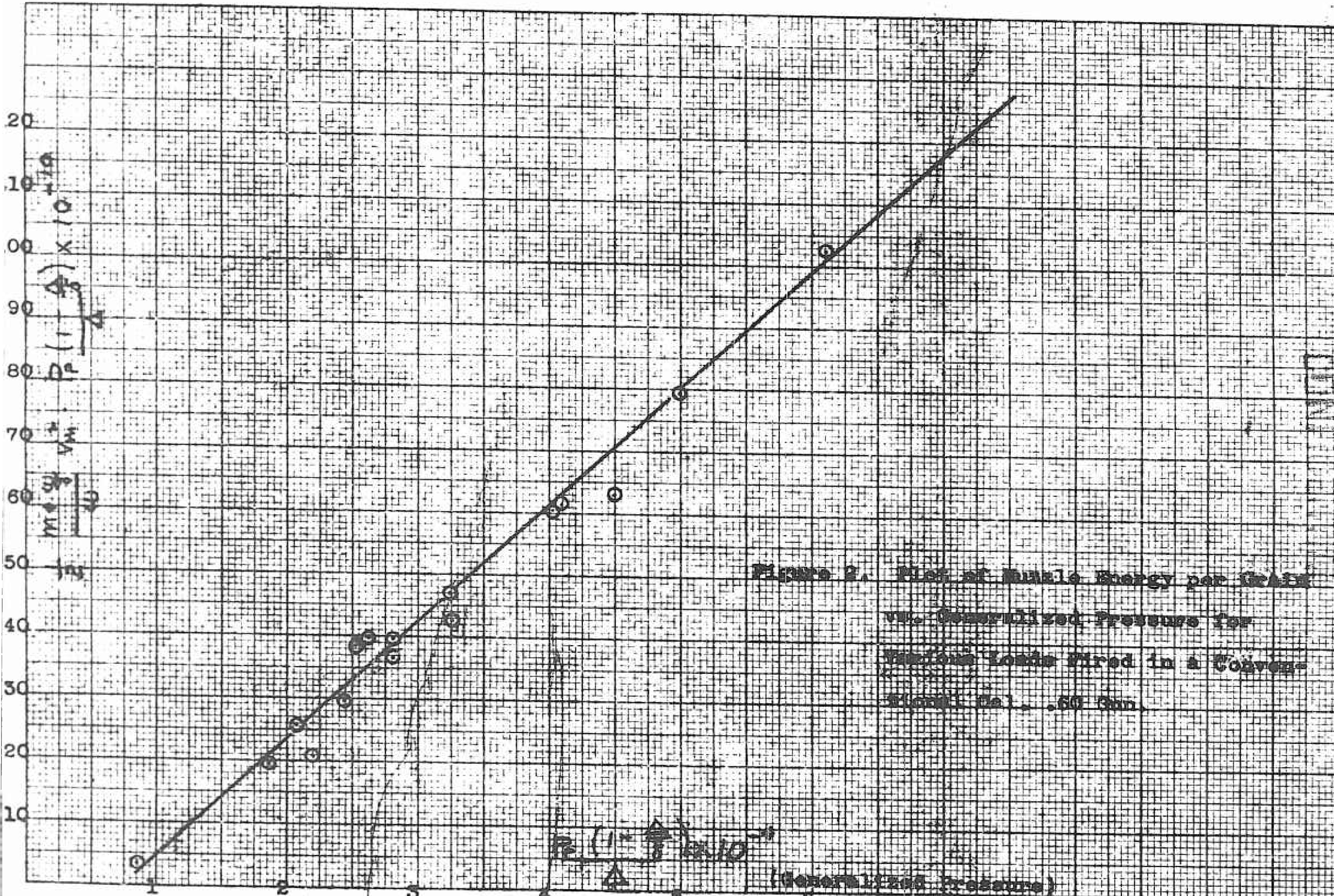

Figure 2. Plot of Muzzle Energy per Grain vs. Generalized Pressure for Various Loads Fired in a Conventional Cal. .60 Gun.

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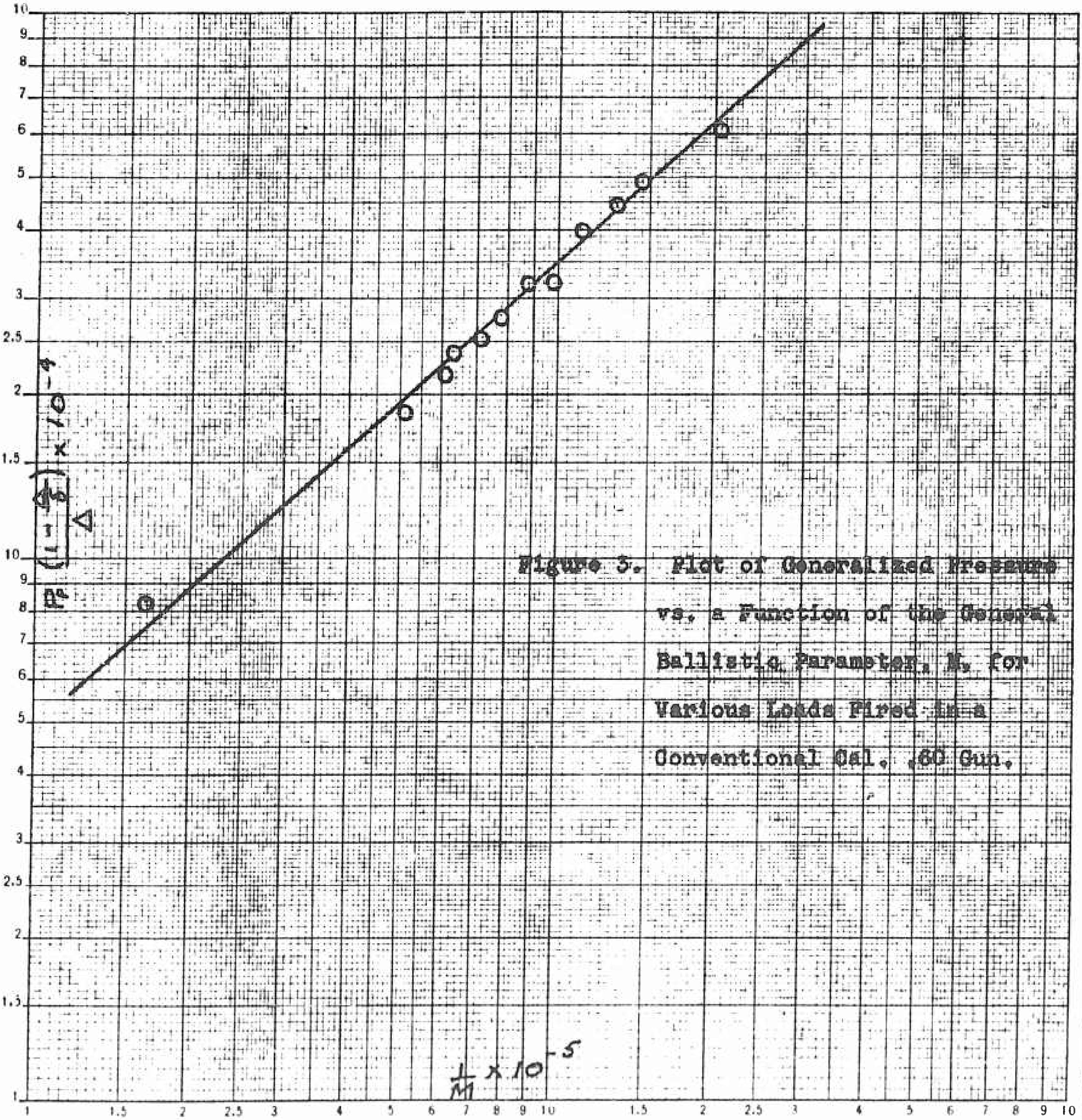

Figure 3. Plot of Generalized Pressure vs. a Function of the General Ballistic Parameter, M, for Various Loads Fired in a Conventional Cal. .60 Gun.

2. The Free Bore Gun

The gun used in the tests under this part of the program had a nominal free bore of 3". Casts were made of the chamber and the first part of the bore. These casts revealed that the actual free bore was 2.944" maximum.

The purpose of this group of tests was to evaluate the effect of free bore on pressure and velocity. Three different values of free bore were employed: 2.944", 2.197", and 1.450". In these tests it was not possible to vary the free bore independently of the case volume.

a. Loading

In tests 19 - 33 the caliber .60 bullet #60T32 was used having a weight of 1200 grains. In tests 34 and 35 700 grain bullets were used. These were made from #60T32 bullets by turning down the noses as described above in this report. In tests 36 and 37 #60T33 bullets having a weight of 1425 grains were used.

In tests 25, 26, 27, 32, 33, 35 and 37 the bullets were seated to the normal depth in the cases. No crimp was employed. The free run was maximum, 2.944". In all other tests the smaller free runs were employed and the bullets had to be loaded separately from the cases. The bullets were inserted to the proper depth in the free bore by means of a special gage designed for this purpose. The cases were then loaded in the chamber in the conventional manner, the mouth of the case being closed by a thin piece of scotch tape in order to prevent the powder from spilling out. In the loads employing the 712 grain chage a cellophane tube was slipped over the case neck to accommodate this charge since the maximum capacity of the caliber .60 case is in the neighborhood of 660 grains.

As described in the last section the powder quickness was varied by blending IMR4996 and IMR4350 powder. A third powder, EX6544, was used in tests 23, 25 and 27.

The reason for the high propellant charge weights in some of the tests should be pointed out. It is clear that in the case of the short free runs - when the bullet is pushed up in the free bore - that the case volume is larger than in the normal round. In order to determine the effect of free bore it is desirable to compare peak pressure and velocity with the results obtained under Part I at the same loading conditions. In order to obtain the same loading density the powder charge weight must be increased.

b. Results

Peak pressure and muzzle velocity were measured in the same manner as Part I. In Table I following page 21 peak pressure, muzzle velocity and loading density are listed for all 19 samples. These are the items 20 to 39 inclusive. Figure 4 on the following page gives the muzzle energy plot for these samples and figure 5 following figure 4 gives the peak pressure plot. These plots are made according to the scheme of equations 65 and 66 on page 20 . Quickness was computed using equation 29 on page 13 and the quickness numbers on page 24. In the velocity plot all the data were normalized to an expansion ratio of 7.20

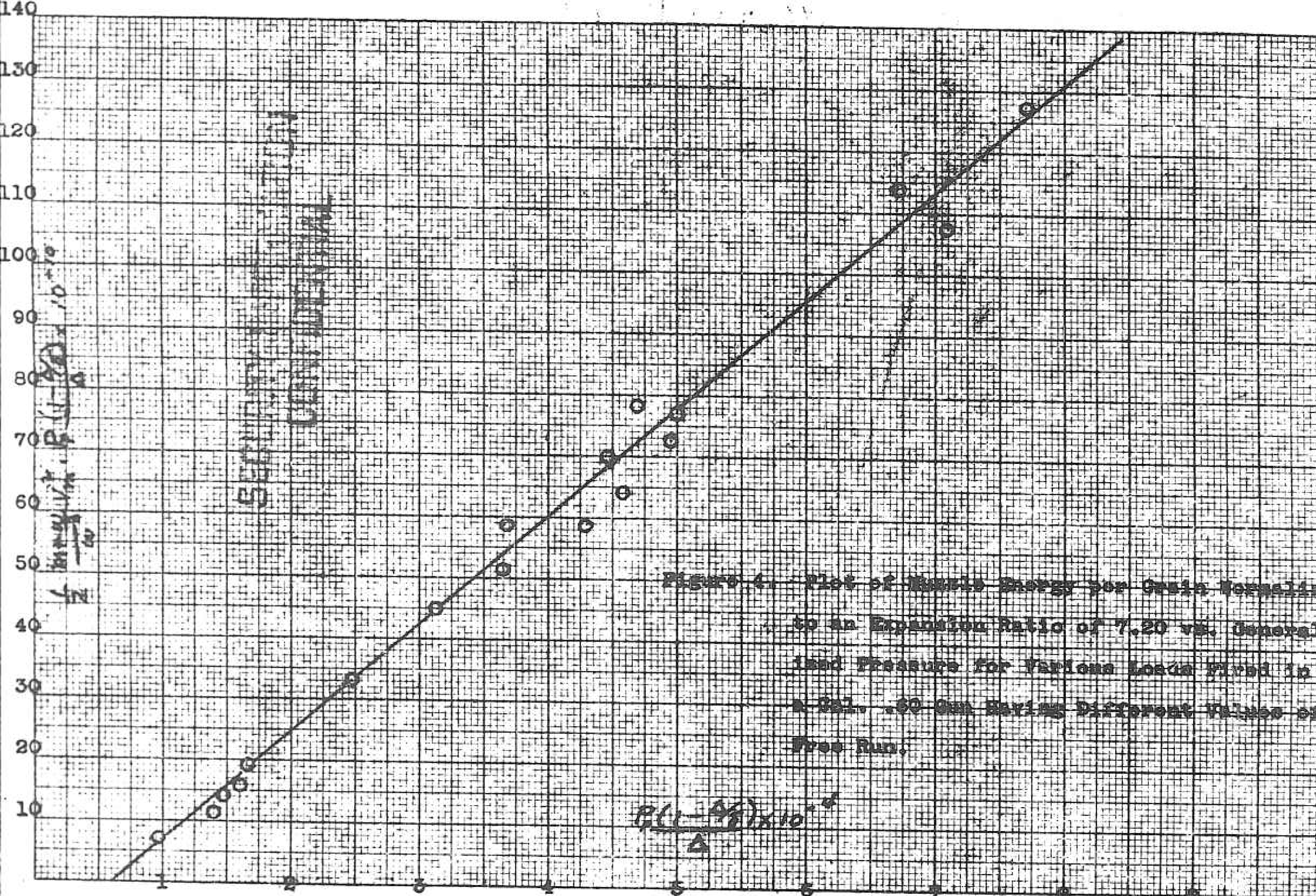

Figure 4. Plot of Muzzle Energy per Grain Normalized to an Expansion Ratio of 7.20 vs. Generalized Pressure for Various Loads Fired in a Cal. .60 Gun Having Different Values of Free Run.

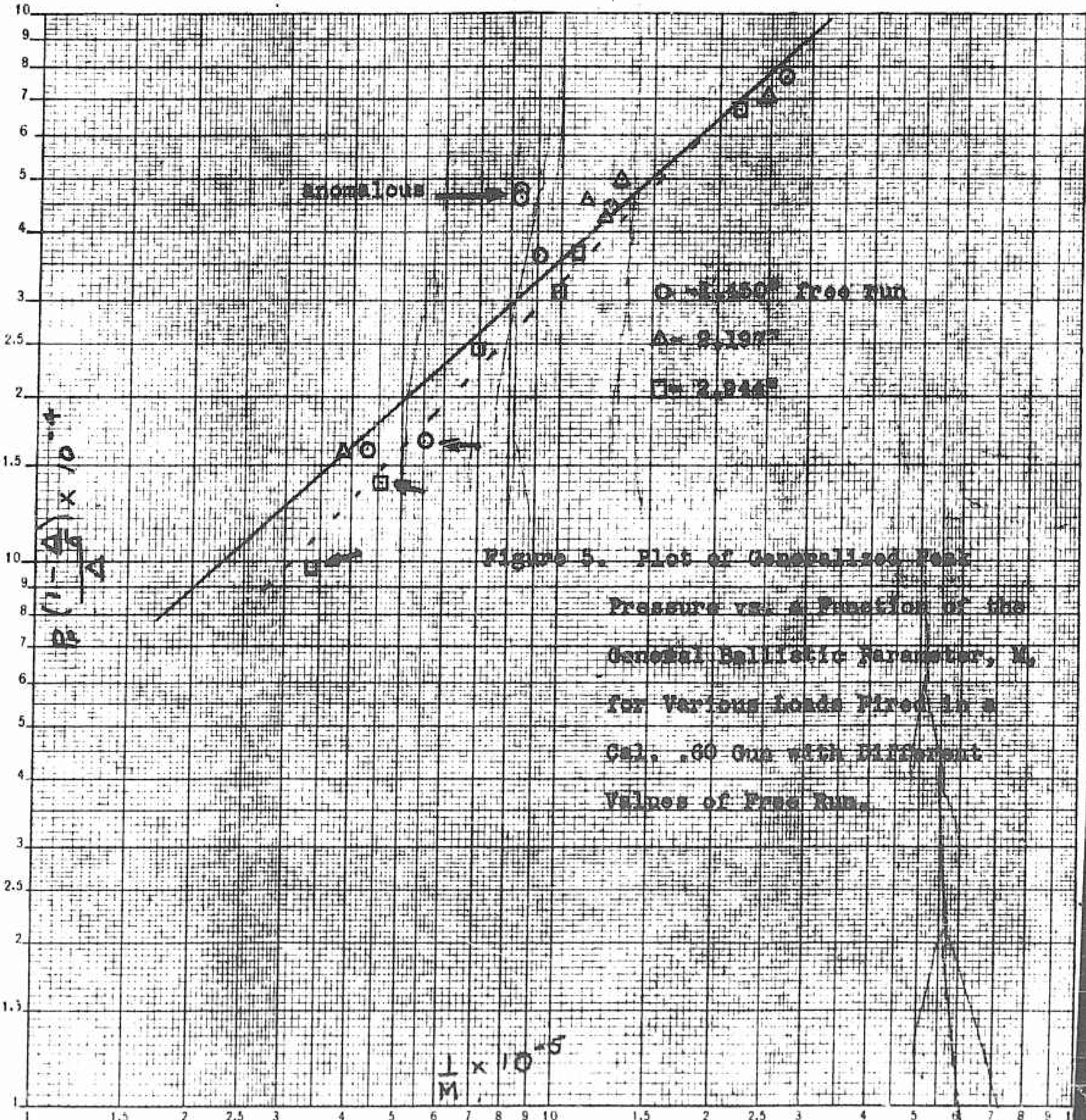

Figure 5. Plot of Generalized Peak Pressure vs. a Function of the General Ballistic Parameter, M, for Various Loads Fired in a Cal. .60 Gun with Different Values of Free Run.

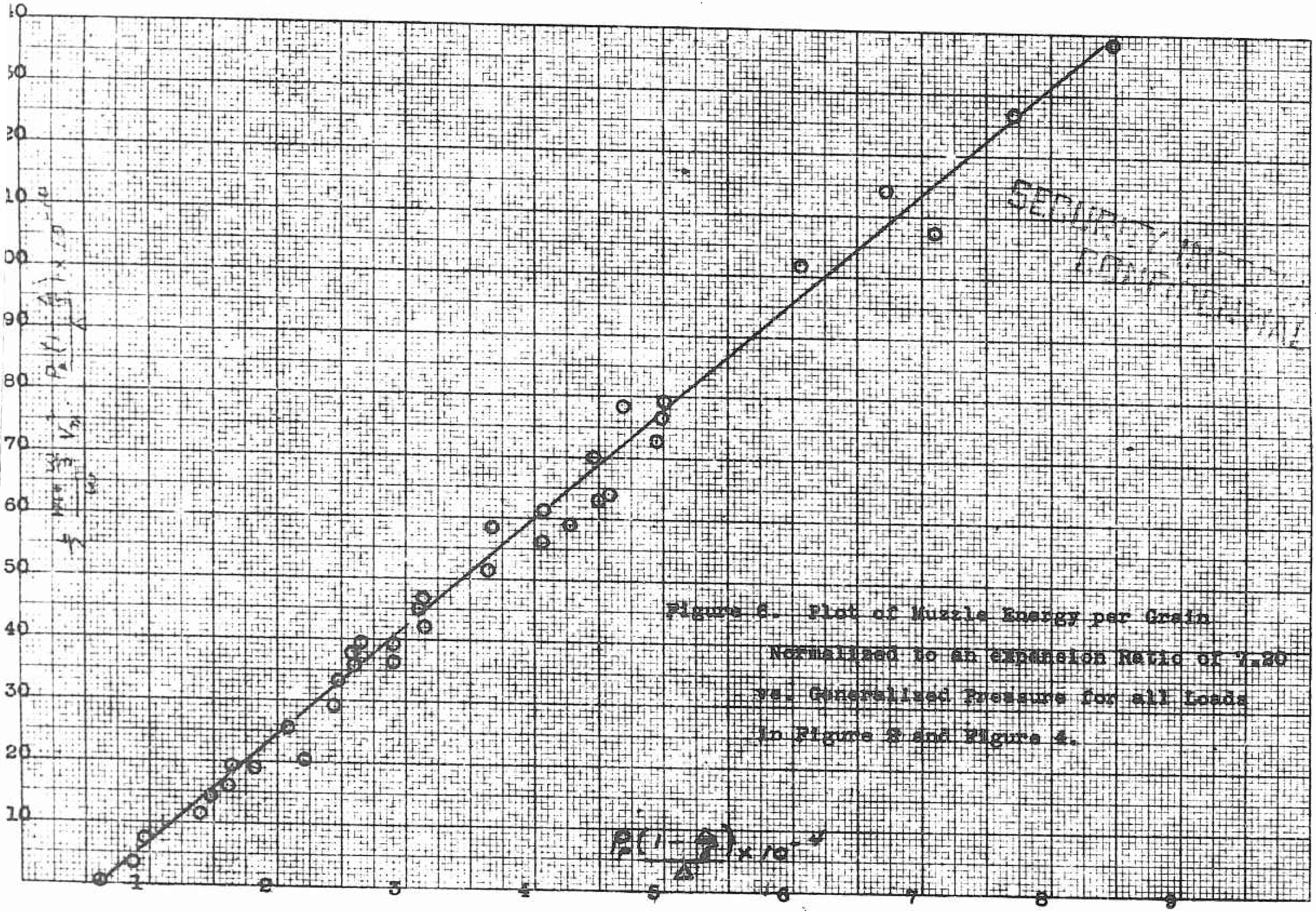

Figure 6. Plot of Muzzle Energy per Grain Normalized to an expansion Ratio of 7.20 vs. Generalized Pressure for all Loads in Figure 2 and Figure 4.

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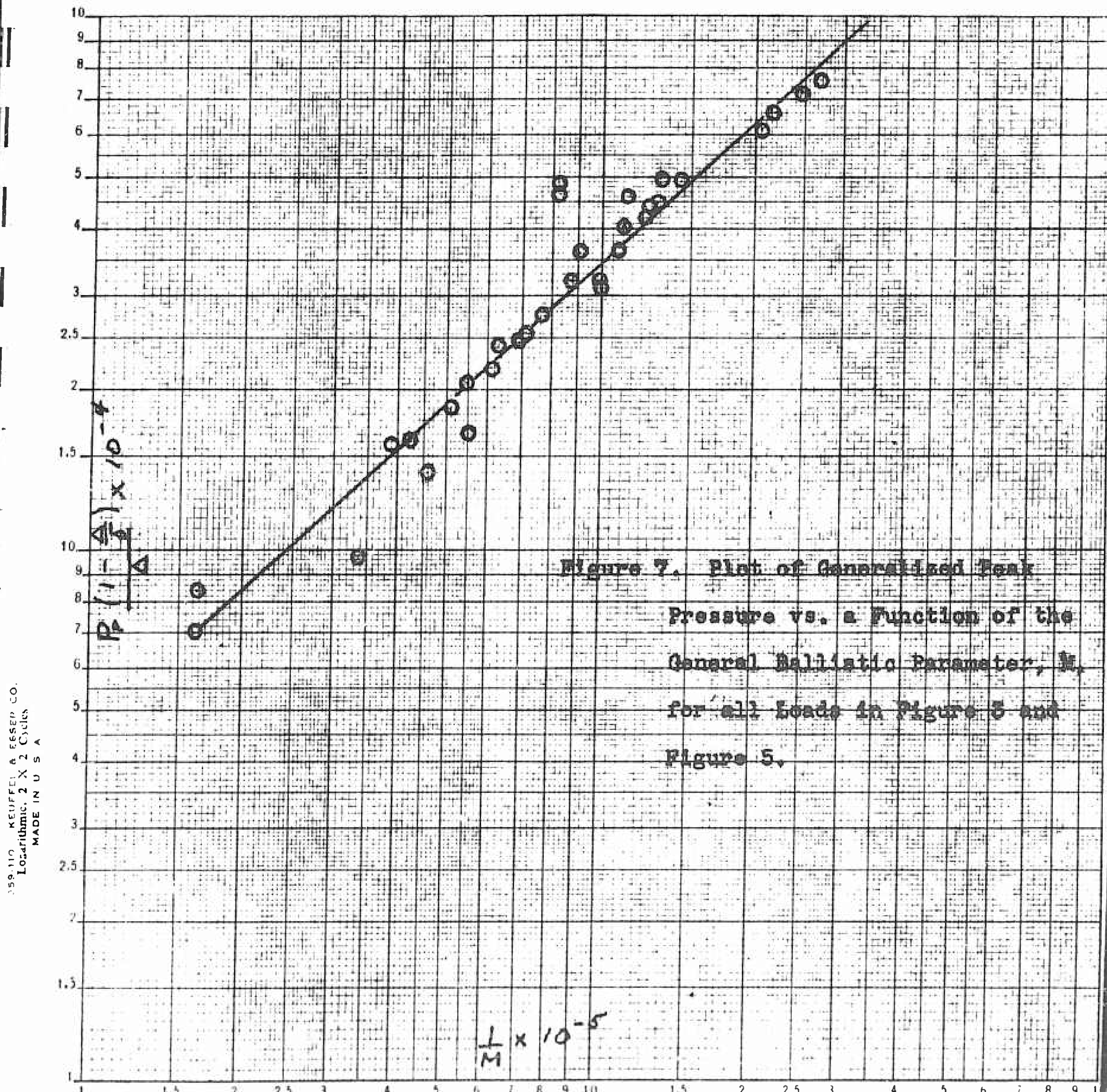

Figure 7. Plot of Generalized Peak Pressure vs. a Function of the General Ballistic Parameter, M, for all Loads in Figure 3 and Figure 5.

by means of the graphs in figure 1.

In figure 6 and figure 7 following figure 5 the curves derived from the data in Part I are drawn for comparison. It can be seen that all of thesamples from Part II that employed the regular caliber .60 chamber volume and maximum free run fall along this curve. We are led to conclude that as much as 3" free run has no effect on the efficiency of the caliber .60 load.

As far as the pressure is concerned some effect of free bore was observed when the free bore was maximum (3"). This is shown in figure 7 where the dotted curve represents a plot of the "maximum free-bore" points. The points at the lower end which deviate most from the curve are all low pressure shots. These are represented by small arrows in the drawing. The pair of anomalous points above the curve also represented by an arrow obviously do not belong to the rest of the population. This anomaly is possibly due to some error in measurement.

In those samples in which the bullet was not seated in the cases, case casualties - neck tears and shoulder separations - occurred, especially at low loading densities and high pressures. Examples of some of these casualties are shown in the photographs in figure 7a on the following page.

It was felt that the necking of the regular caliber .60 cases was reponsible for these casualties. Hence some cases were cut off at the 1.050" diameter - just at the shoulder (see drawing SKRL-12-1652-6 following page 30).

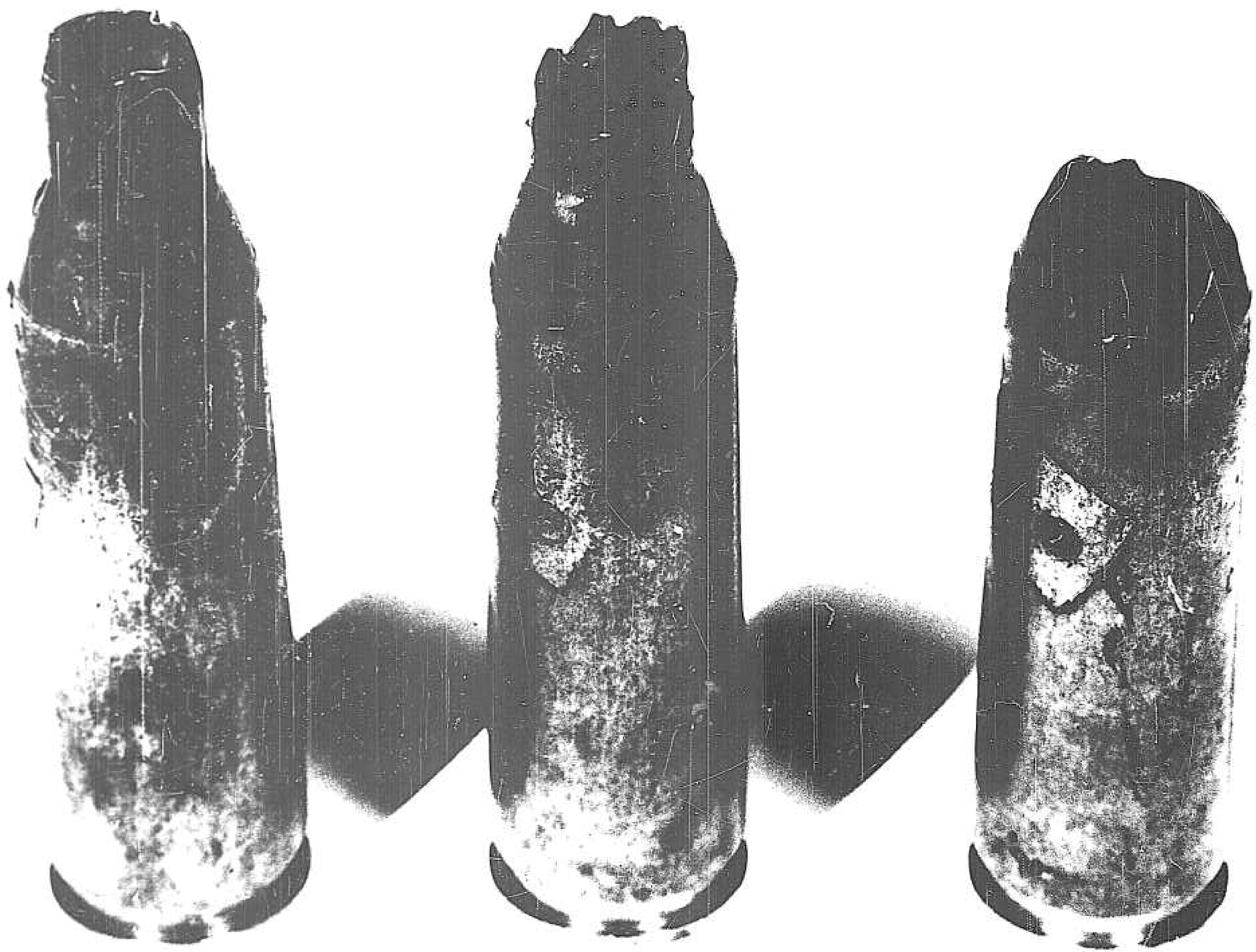

Fig. 7a

This made the overall case length about 3-5/16". These cases were loaded with a charge of 530 grains of powder of which 330 grains was IMR4996 and 200 grains was IMR4350, to give a peak pressure of 60,000 psi. The firings were done in the free bore gun with maximum free volume between the bullet base and the case mouth. The loading density was .658. As in the previous tests in the free bore gun the bullets were loaded separately, being pushed up into the free bore with the special gage designed for this purpose. No casualties - mouth splits, separations, etc. were observed. These tests showed that the casualties previously obtained were due to case chape of the standard caliber .60 case. Hence, in the design of the cartridge to be used in the unconventional gun a straight wall case with slight taper should be used.

3. Gun with Change in Gas Flow Direction

It was decided to employ a change in gas flow direction of 90° since this would represent the extreme condition in any proposed design. This represents the main design requirement for the special receiver used in this part of the project. The gases must change their flow direction between the mouth of the case and the base of the bullet, the purpose of the experiment being to determine whether such a change in gas direction affects the ballistics of the load and the erosion of the barrel. Such a receiver was designed. In the following paragraphs the important features of this design will be discussed. Reference should be made to drawings CRL-1542, DRL-1543 and CRL-1544 at the end of this report. An "exploded" photograph of the completed breech fixture and barrel is shown in figure 8.

a. Bore between Case Mouth and Bullet Base

It was felt that a distance between case mouth and bullet base longer than 2" would be impractical in the final design of the gun. The diameter of this section was arbitrarily chosen equal to the diameter of the free run in the barrel so as to avoid constriction or expansion of the bore which would complicate the gas flow. A 90° angle between bore axis and chamber axis was chosen as this represents the most extreme condition that would be encountered in a practical gun design.

b. The Receiver Block

The receiver block is shown in drawing CRL-1544 at the end of this report. Provision is made to use the Frankford Arsenal pressure gage and piston (AXL-7670). Gas sealing is obtained at the breech end by obturation of the cartridge case and at the barrel end by an O-ring and a raised boss on the barrel face. (DRL-1543)

c. The Barrel

The barrel used in these tests was a regular caliber .60 barrel with the chamber cut off. Minimum free-bore (see drawing DRL-1543 at the end of this report) was used; the rifling begins with a short lead at the breech end of the barrel.

d. Loading of the Gun

Bullets and cartridge cases must be separately loaded in this gun. The barrel is always clamped; the receiver block is unscrewed in order to load the bullet into the barrel.

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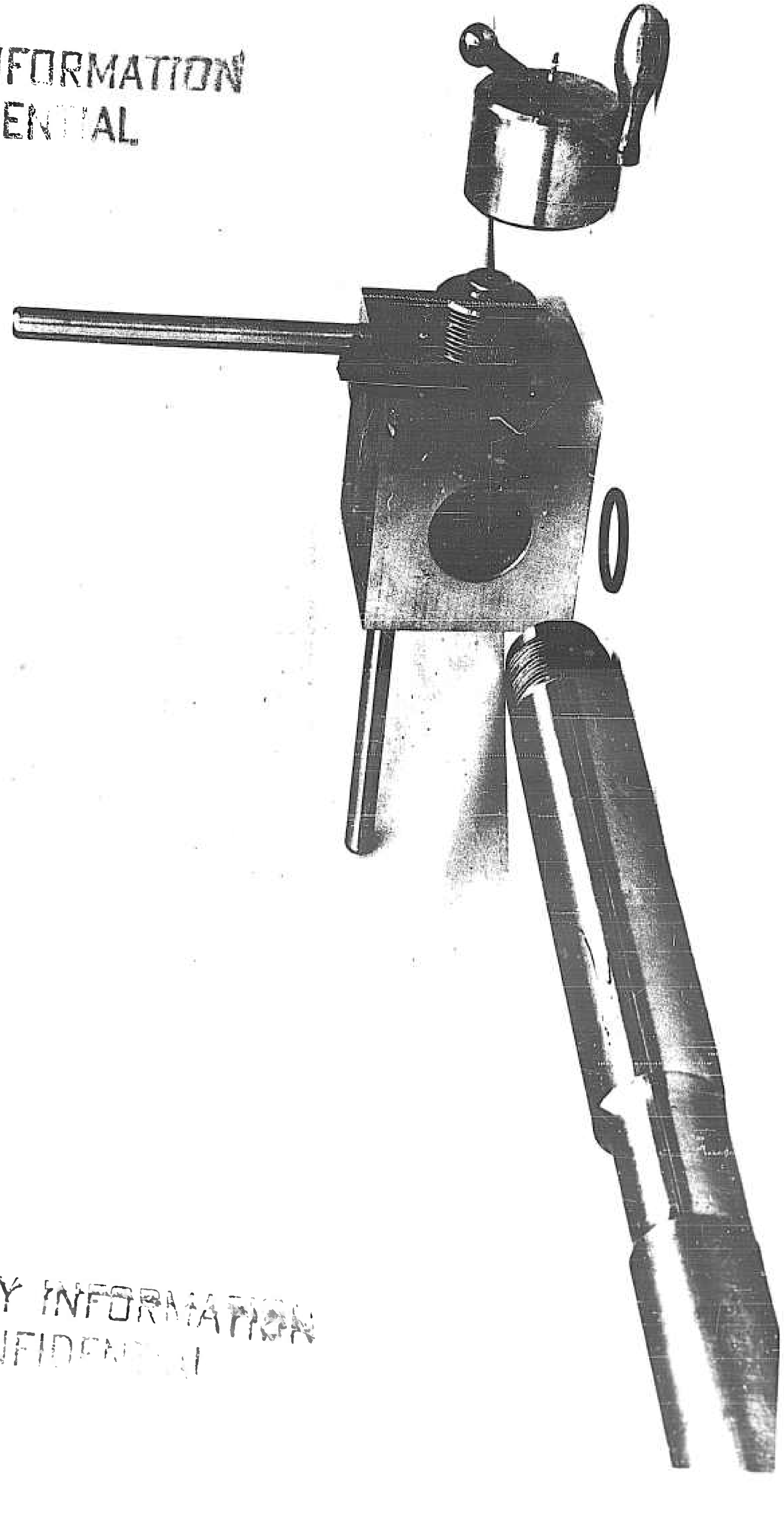

Fig. 8

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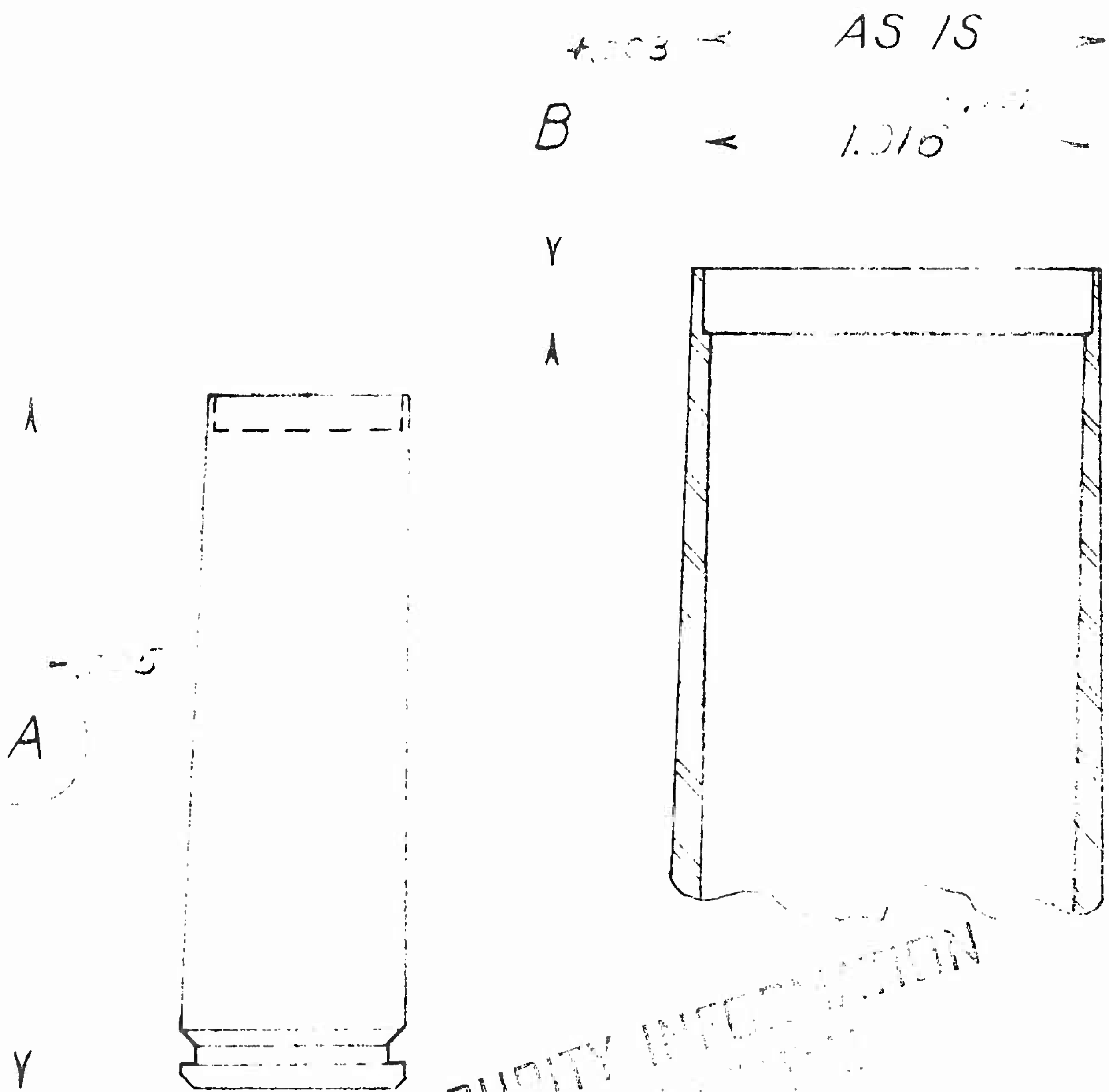
Closure on the breech end of the cartridge case is provided by the regular caliber .60 test barrel breech.

e. Test Firing of the Gun

A few preliminary test rounds were fired in this gun. Difficulty was encountered in detaching the receiver block from the barrel. This constituted a serious defect since the operation must be carried out every time the gun is loaded. In addition severe galling of the metal surfaces where the barrel and receiver were in contact resulted.

To eliminate these difficulties the 2.2505" diameter of the barrel seat in the chamber block was increased by .005" (refer to drawing CRL-1544 at the end of this report). Also a sling was fitted to the chamber block so that the block could be suspended from the ceiling of the gun bay in alignment with the bore axis of the barrel - the latter remains fixed in the gun rest. The sling is designed so as not to interfere with the rotation of the chamber block when the latter is unscrewed from the barrel. The sling eliminates the binding of the threads due to the heavy weight of the chamber block.

It was found that the rubber eroded from the O-ring contributed to the galling of the metal surface. Hence, some shots were fired omitting the O-ring and depending only on the pressure seal effected by the metal boss. The surfaces were lubricated with "lubriplate". Such tests showed that the use of the O-ring was unnecessary. The boss provides a much better gas seal than anticipated. Even at pressures of 83000 psi no serious gas leakage was observed.



	DIMENSIONS A	B
CASE I	3.305	.090
CASE II	3.305	.150
CASE III	3.305	.175

ALL CORNERS ARE SHARP

REMINGTON ARMS CO., INC., — BPT., CONN.
RESEARCH & DEVELOPMENT DEPT.

COUNTER[illegible]

[illegible] CLOSURE

DRAWN Weymouth | APP'D | DATE 12-16-52

SKRL- 12-1[illegible]

f. Ballistic Test Results

Cut-off caliber .60 cases (drawing SKRL-12-1652-6 following page 30) and #60T32 bullets having a weight of 1200 grains were used in the tests done in this part of the test program. These tests represent items 39 to 44 in Table I following page 21. The volume of the chamber behind the bullet base was measured and found to be 52.47 cc. In samples 43 and 44 the cases do not have the capacity to accommodate the large powder charges specified in the table. Hence, part of the charge was poured into the case to fill it and the remainder poured into the chamber so as to fill the right angle section before the cartridge was inserted into the chamber.

The velocity and peak pressure were measured in the manner mentioned on page 22. A plot of muzzle energy and peak pressure according to the scheme of equations 65 and 66 on page 20 is given in figure 9 and figure 10 on the following two pages.

When these data are combined with the data obtained in the other parts of the program the general curves for muzzle energy and peak pressures given by figures 11 and 12 following page 32 are obtained. The curves contain all the data obtained in the project. It should be pointed out that all the data have been "normalized" to an expansion ratio of 7.20. In the unconventional gun, for example, the expansion ratio is only 5.88 due to the short length of the barrel and the large chamber volume. In Figures 13 and 14 the velocity is plotted as a function of the propellant charge weight to

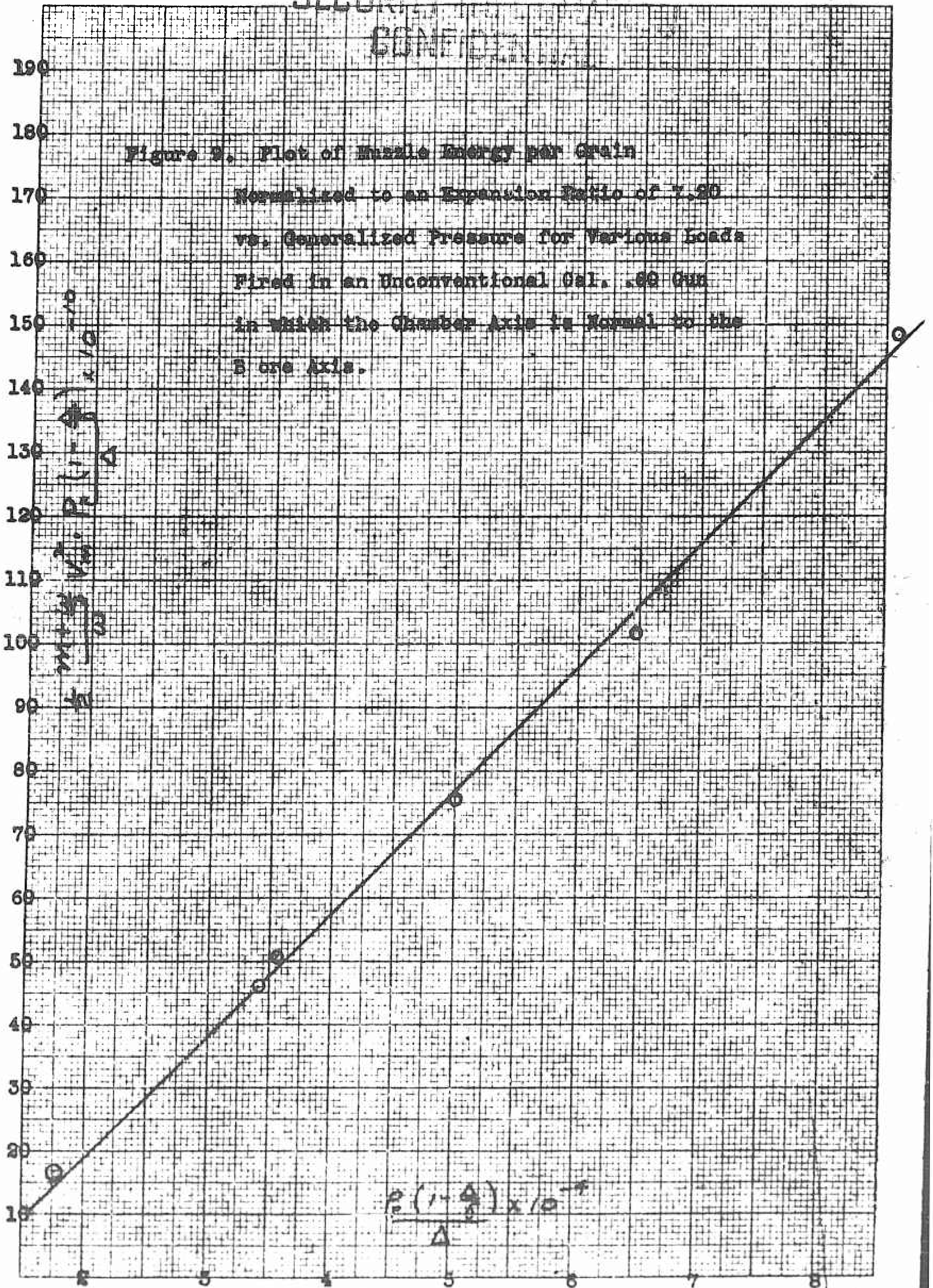


Figure 9. Plot of Muzzle Energy per Grain Normalized to an Expansion Ratio of 7.20 vs. Generalized Pressure for Various Loads Fired in an Unconventional Cal. .60 Gun in which the Chamber Axis is Normal to the Bore Axis.

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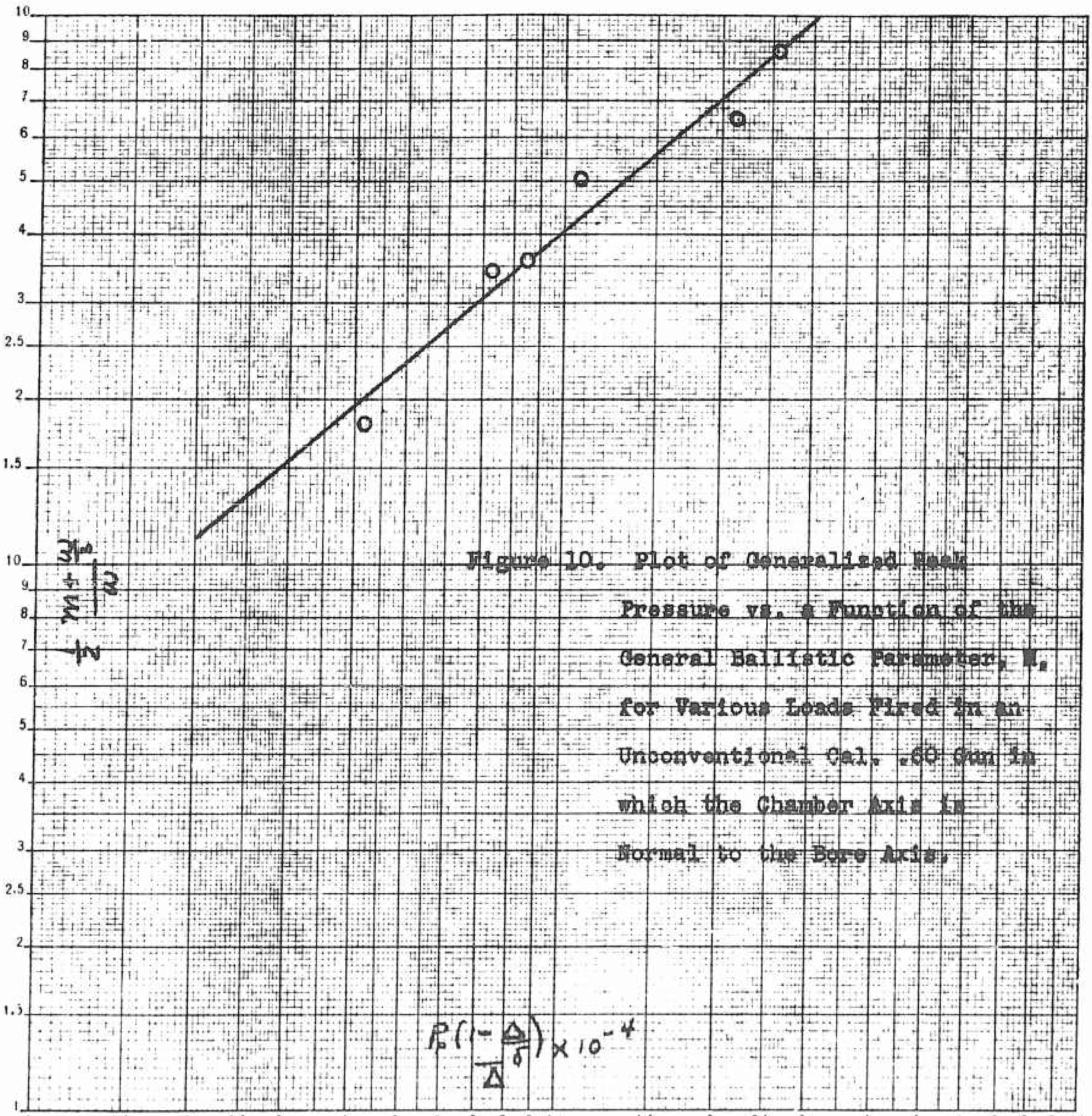


Figure 10. Plot of Generalized Peak Pressure vs. a Function of the General Ballistic Parameter, M, for Various Loads Fired in an Unconventional Cal. .60 Gun in which the Chamber Axis is Normal to the Bore Axis.

"fictitious projectile weight", $m + w/3$ ratio for various loading densities at pressures of 40,000, 50,000, 60,000 and 70,000 psi.

An examination of the general curves in figures 11 and 12 will reveal that the results obtained with the unconventional gun are consistent with previous firings. Hence, it can be concluded that under these circumstances the effect of change in direction of gas flow on ballistics, that is to say, peak pressure and muzzle velocity, is negligible.

II. EROSION IN GUN WITH CHANGE IN GAS FLOW DIRECTION

Approximately 500 rounds of ammunition were loaded for use in these erosion tests. The cartridge cases were regular caliber .60 cases, cut off and counterbored (see drawing SKRL-12-1652-6 following page 30). These cases were loaded with a duplex load consisting of 377 grains of IMR4996 powder and 148 grains of IMR 4350 powder. The total charge was 525 grains. After loading, a closure disc* made of .060" thick Nixon #666 cellulose nitrate was inserted at the case mouth. The case mouth was crimped over this disc and flattened with an ironing punch. Caliber .60 bullets #60T32 having a weight of 1200 grains were used. This load was designed to give a pressure of about 58000 psi in the unconventional test gun with a muzzle velocity of about 3200 feet per second.

A. Method of Evaluating Erosion

Originally it was planned to determine the erosion or the right angle section between the chamber volume and the

* For a discussion of closure discs see Part III, page 35 of this report.

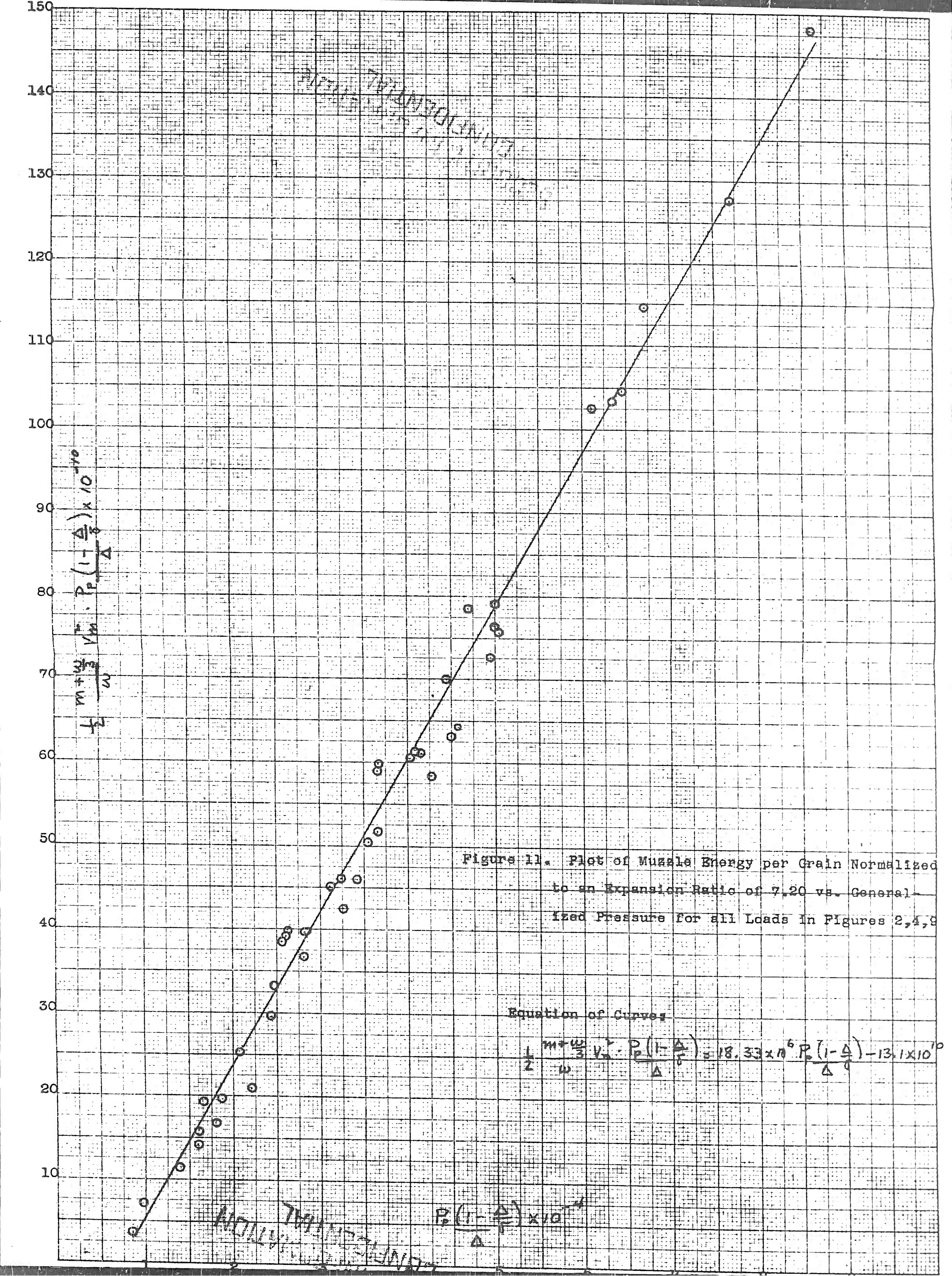


Figure 11. Plot of Muzzle Energy per Grain Normalized to an Expansion Ratio of 7.20 vs. Generalized Pressure for all Loads in Figures 2,4,9

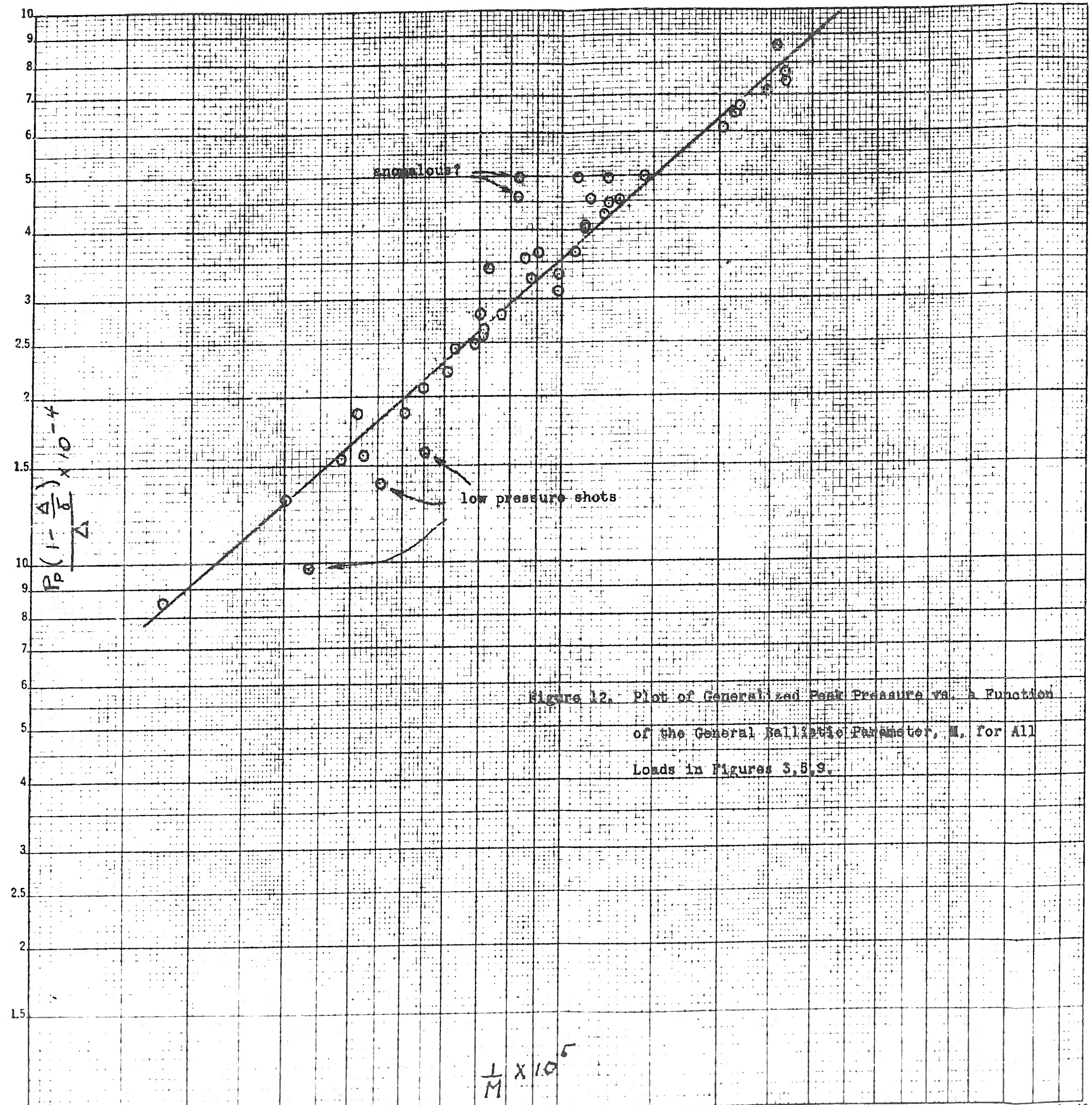


Figure 12. Plot of Generalized Peak Pressure vs. a Function of the General Ballistic Parameter, M, for All Loads in Figures 3,5,9.

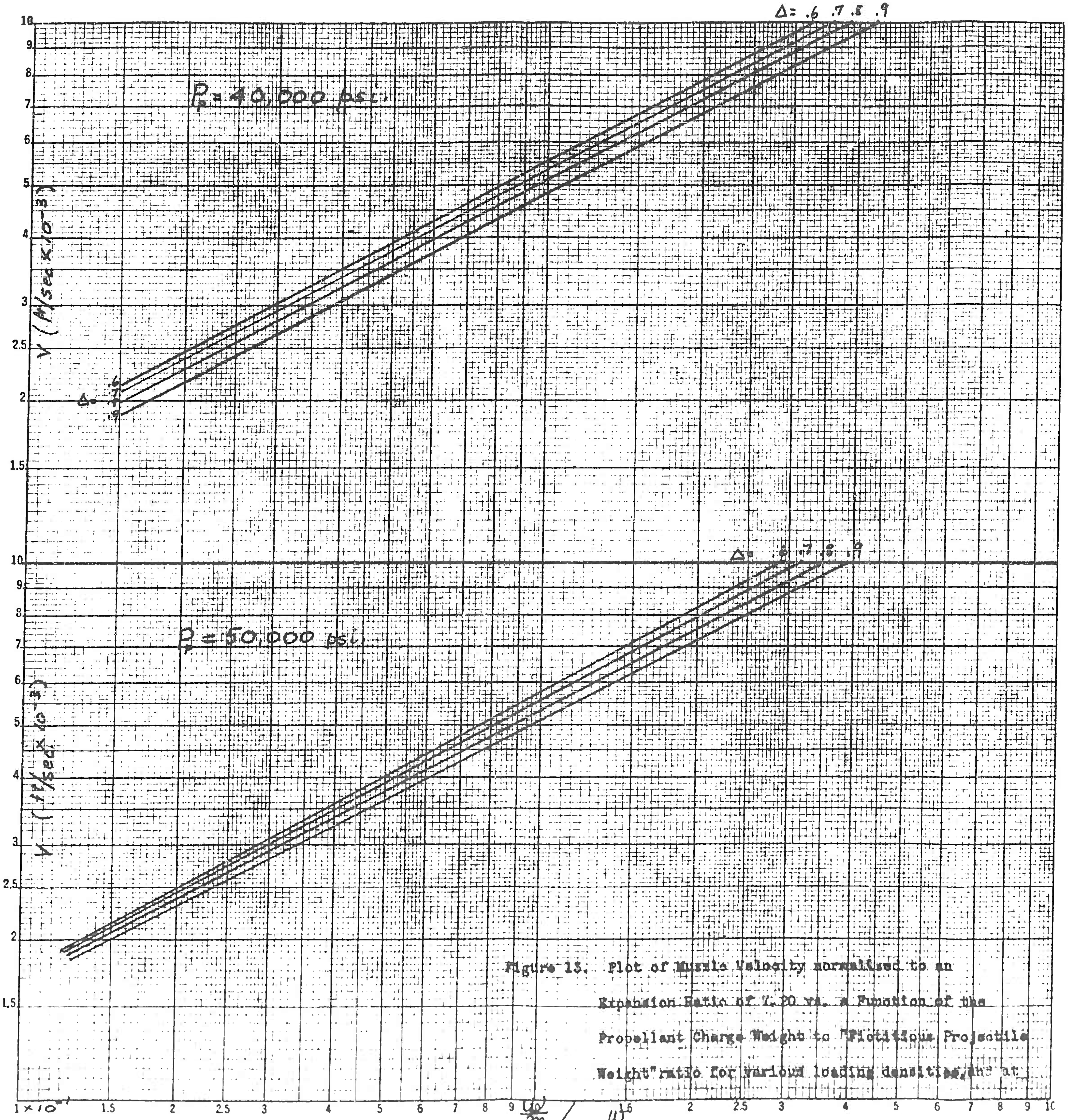


Figure 13. Plot of Muzzle Velocity normalized to an Expansion Ratio of 7.20 vs. a Function of the Propellant Charge Weight to "Fictitious Projectile Weight" ratio for various loading densities and at

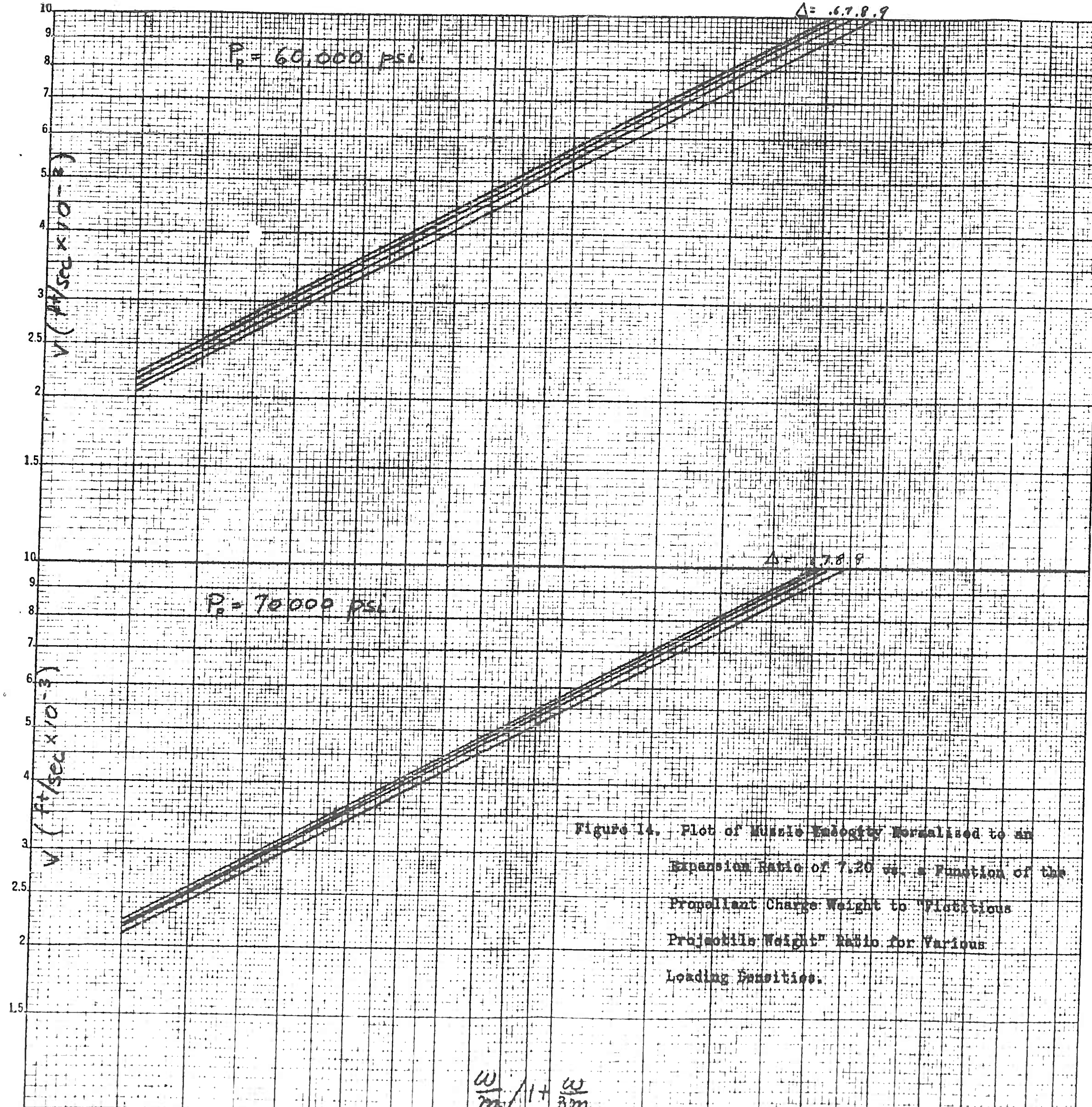


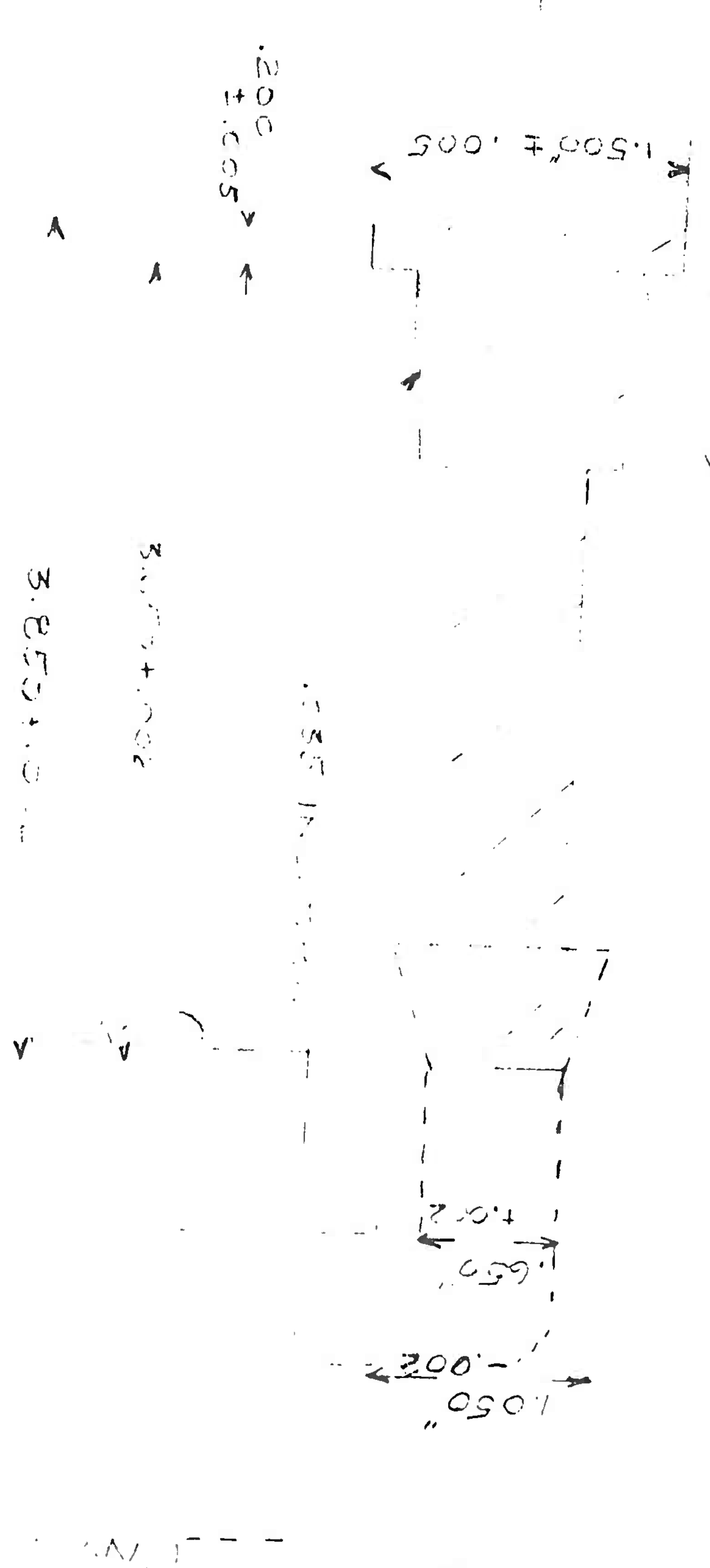
Figure 14. Plot of Muzzle Velocity Normalized to an Expansion Ratio of 7.20 vs. a Function of the Propellant Charge Weight to "Fictitious Projectile Weight" Ratio for Various Loading Densities.

bore of the gun by measuring the volume of this section periodically during the firing of the test. In this way it was thought that a plot of volume vs. number of rounds fired could be drawn and the extent of erosion determined. A plug seal was designed which enabled the volume measurement to be confined to the right angle section of the bore in order to reduce the percent error of the measurement (see SKRL-5-853-2 on the following page). However, upon actual trial this method proved to be too inaccurate to evaluate the progress of erosion in the gun. For one thing the accuracy of the measurement depends in large part on the reading of a meniscus at a section where the diameter is .600". This cannot be done with sufficient accuracy. Also this method ignores surface changes which are of importance in detecting erosion effects.

In view of these limitations the above method of evaluation was abandoned and it was decided to rely entirely on visual inspection of the bore and chamber. To provide a permanent record, photographs were taken before starting the firing of the test to establish the initial condition of the barrel and thereafter whenever important erosion effects were observed.

B. Results of Tests

In order to facilitate the description which follows the following terminology will be used. Referring to figure 15 on the following page observations made from breech end will be termed "observations at station A" and those from the barrel end "observations at station B". The inside curvature of the right angle section will be called X and the outside will be



MAT'L - BRASS

REMINGTON ARMS CO., INC., — BPT., CONN.
RESEARCH & DEVELOPMENT DEPT.

PLUG SEAL

[illegible]

DRAWN L. G. S[illegible] | APP'D | DATE 5/1/53

SKRL- 5-[illegible]53-2

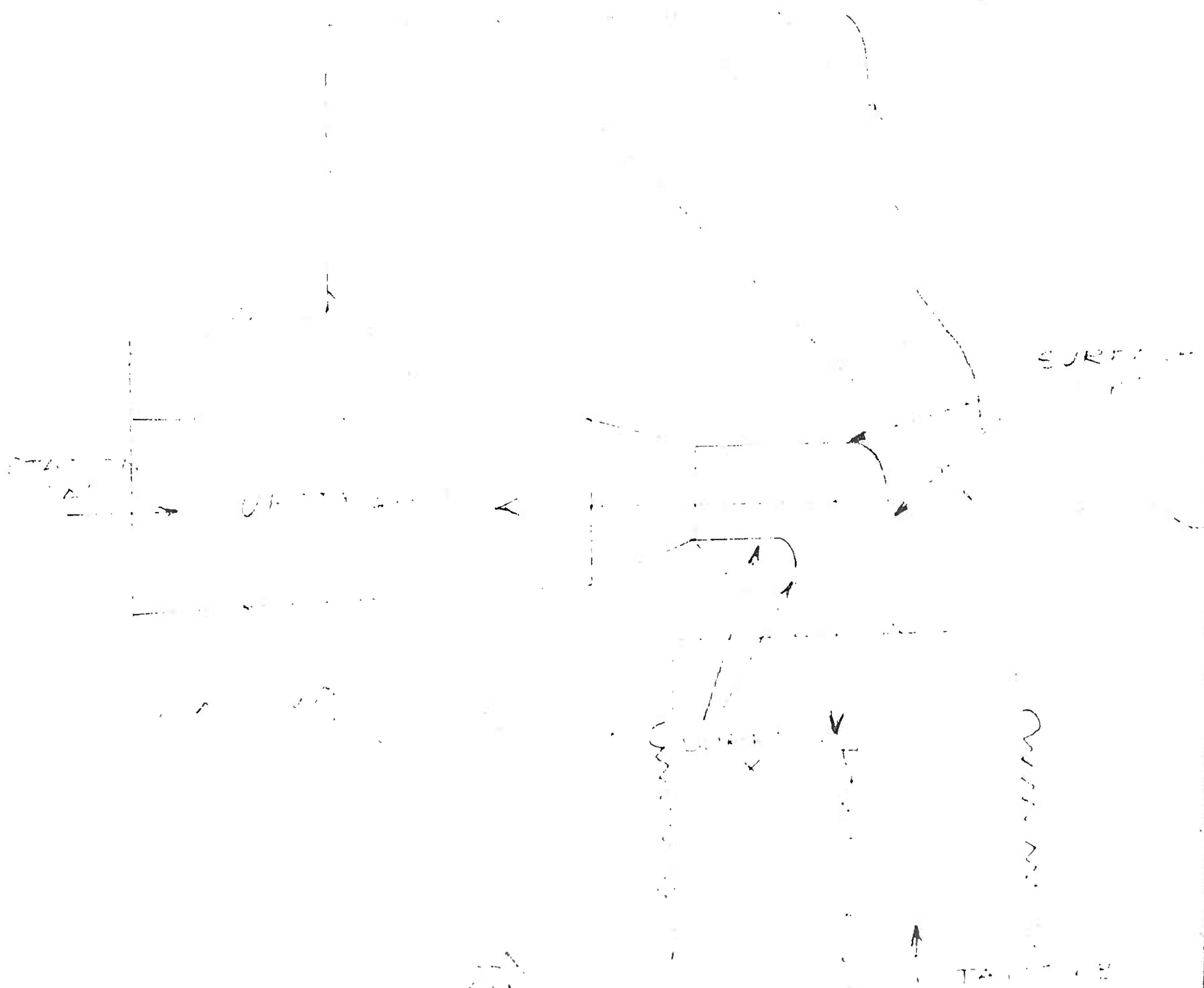
called Y. The terms "up-stream" and "down-stream" are defined in the figure on the following page.

At the beginning of the test the gun had a previous history of 65 rounds. To establish the initial condition of the gun for future comparisons a photograph was taken of the Y surface of the bore from station A. This is shown in figure 16 following figure 15. It can be seen that slight pitting of the metal surface has started.

Fifty additional rounds were then fired through the gun. A photograph, similar to that in figure 16, was taken from the same position - station A. It can be seen that at this point - total number of rounds 115 - the pitting in the Y surface has become more pronounced (figure 17).

As firing continued the Y surface did not change appreciably in appearance but two deep erosion grooves began to form downstream on surface X. These grooves became progressively deeper after each shot. After an additional 25 rounds had been fired - total number of rounds 140 - the test was halted. A photograph was taken from station B of the downstream section of the bore in silhouette. This is shown in figure 18. By this time the grooves had a depth of approximately 1/16" and a width of 1/8".

It was also noted that the breech end of the barrel was beginning to show signs of erosion. When the barrel is screwed into the receiver block the pressure of the flat surface of the breech end of the barrel against the corresponding surface of the receiver provides the gas seal. Before the barrel is



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RESEARCH & DEVELOPMENT DEPT.

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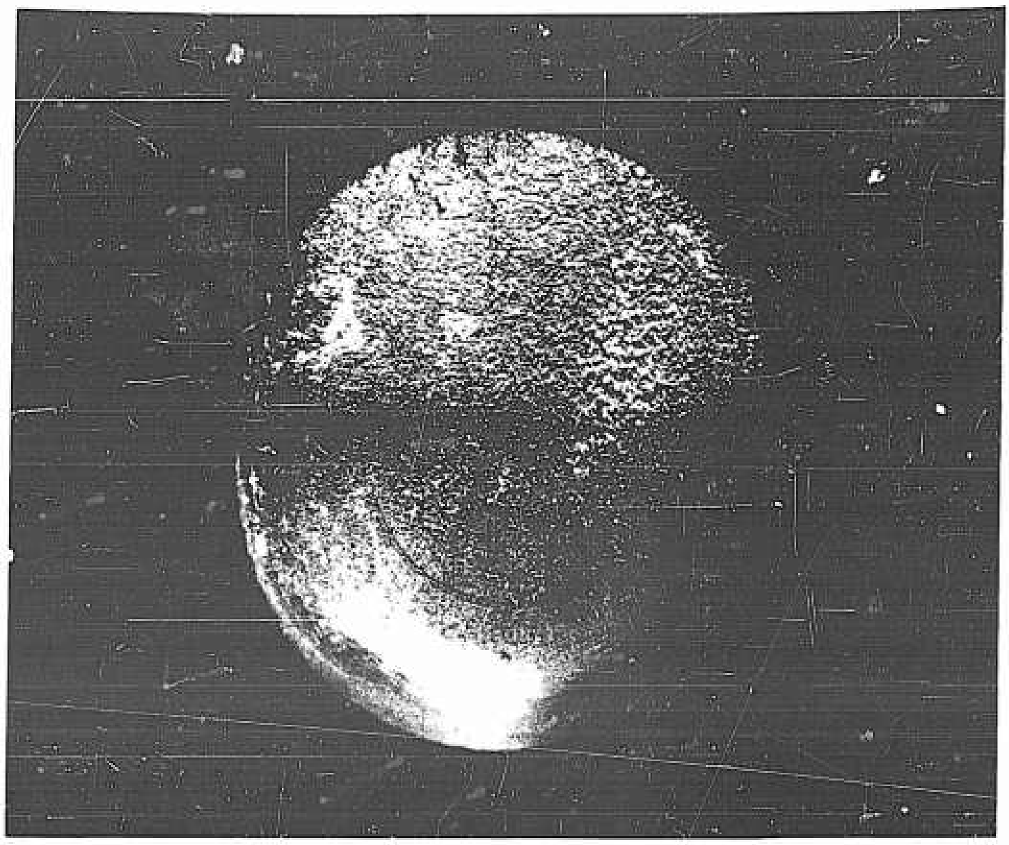


Figure 16

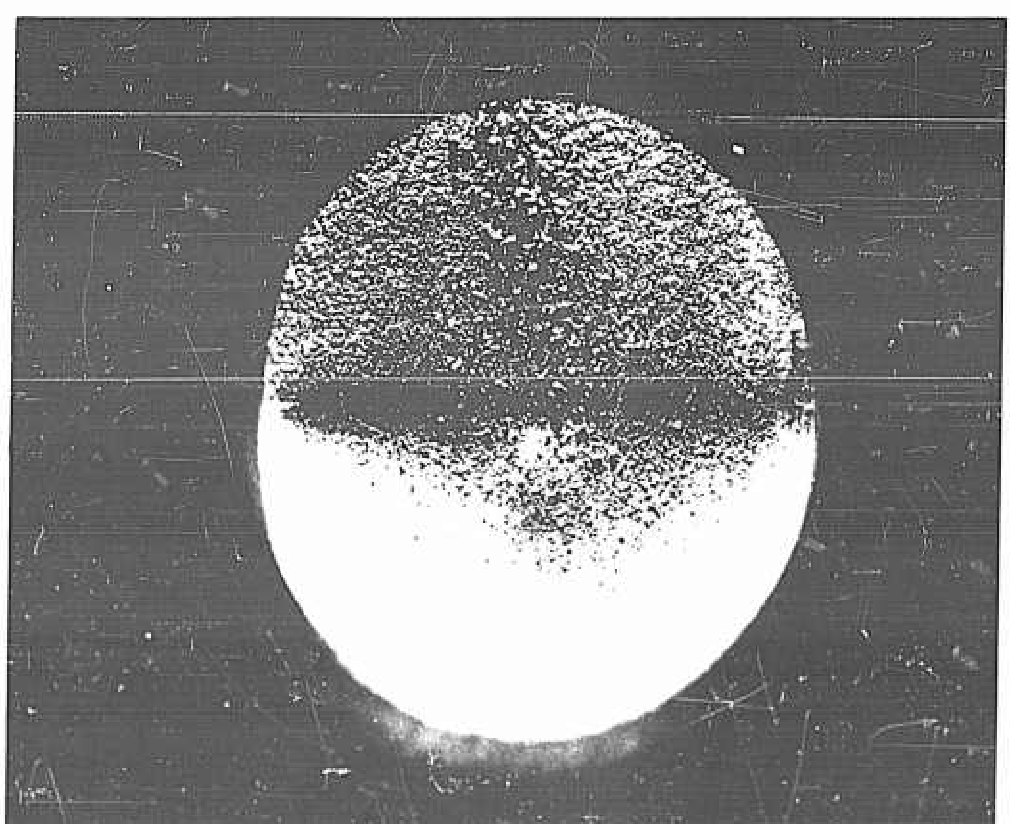


Figure 17

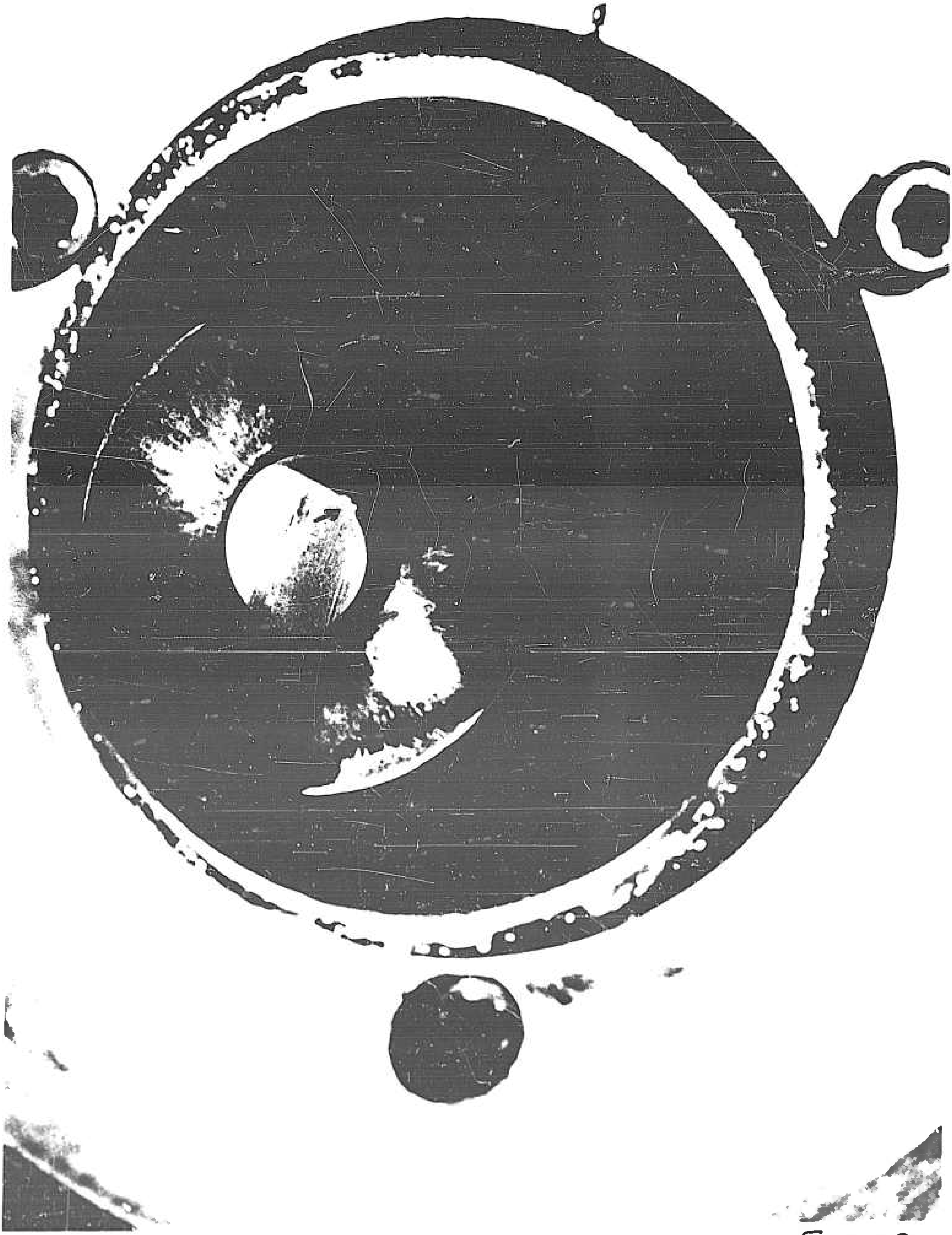


Fig. 18

screwed into the receiver the bullet is breech loaded into the barrel to its full depth so that the bullet heel is flush with the breech end of the barrel. Erosion was beginning to take place about the bullet seat. Continuation of erosion in this area would eventually destroy the gas seal between barrel and breech with the consequent destruction of the threads and machined surface in this region.

At this point - 140 rounds - an adequate estimate of the extent of erosion had been formed. There seemed to be no point in risking a severe gas leak by continuing the firing and hence further testing was discontinued.

It should be pointed out thatthe velocity of each round was measured during the firing. There was no falling off in velocity as erosion became more pronounced.

The steel used in the construction of the receiver used in these tests was 4140 heat treated.

III. CASE CLOSURE

In the original statement of the objectives of this project and as a result of further discussions with Frankford Arsenal personnel, the following specifications were set up on case closure.

1. The closure should not employ materials which might foul the barrel or lodge in the bore.

2. The closure should be ballistically efficient, that is to say, should not result in loss of muzzle velocity, or give excessive pressures or poor ignition.

3. It should not contribute to muzzle flash or streamers of luminous particles at the muzzle.

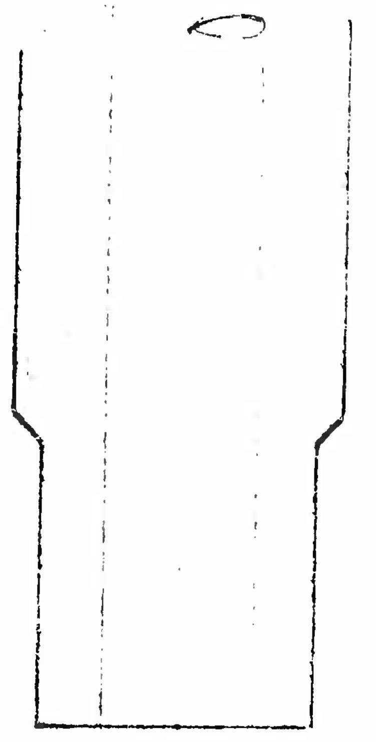
A. Combustibility Tests

In order to retain the powder charge in the case under normal conditions of firing and handling, various methods of closure were considered. These included the "star crimp", the knurl, the dimple or indent, the stake, and the counterbore. The closure has to be moisture-proof and capable of withstanding rough handling besides satisfying the requirements listed above.

With the exception of the star crimp, all of the closures mentioned would require a combustible card or disk and, in this regard, it was believed that either cellulose nitrate (Pyralin) or Ballistite might meet the requirements.

In the initial investigation, efforts were confined to counterboring the case mouths to provide a seat for cellulose nitrate plastic disks blanked from sheet stock of two thicknesses, .025" and .040". The blanking punch and die are shown in SKRL-1 on the following page. The test cases were loaded and the disks inserted by hand after which the counterbored metal was rolled over and flattened by means of two punches as shown in SKRL-2 following SKRL-1. Both the blanking and the crimp closure operations are adaptable to practical production methods.

Tests of these shells indicated that a Pyralin disk of this diameter and as thick as .040" is entirely consumed in firing. However, in view of the fact that firing tests also developed a tendency to score and split the case at the mouth, it was decided that a closure made in the area of the shoulder would be more feasible. In fact these initial tests were of an



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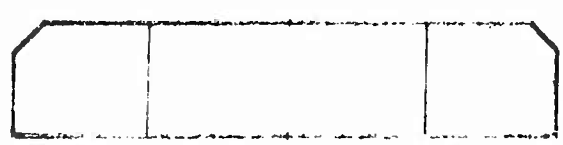

REMINGTON ARMS CO., INC., — BPT., CONN.
TECHNICAL DEPARTMENT

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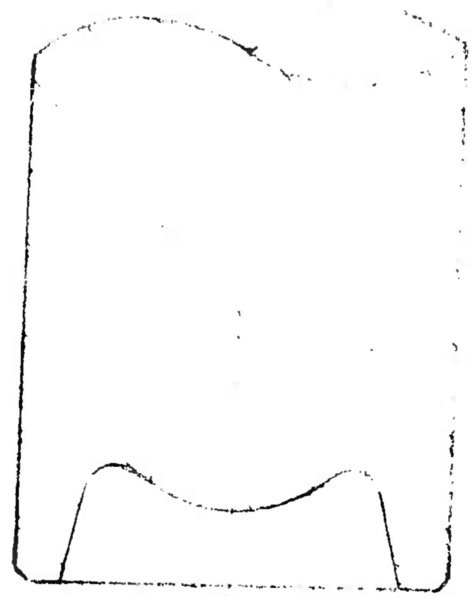

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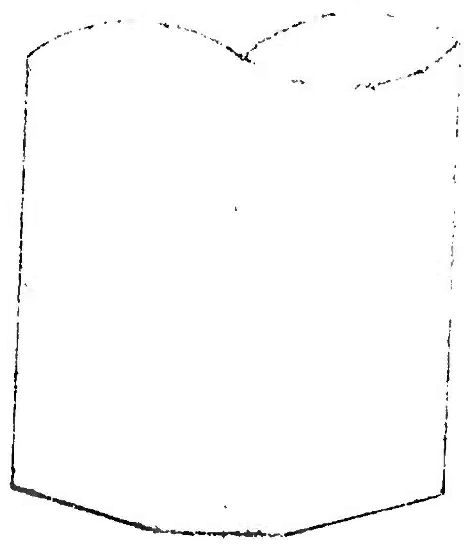

FLATTENING PUNCH

SCALE: 2X

REMINGTON ARMS CO., INC., — BPT., CONN.
TECHNICAL DEPARTMENT

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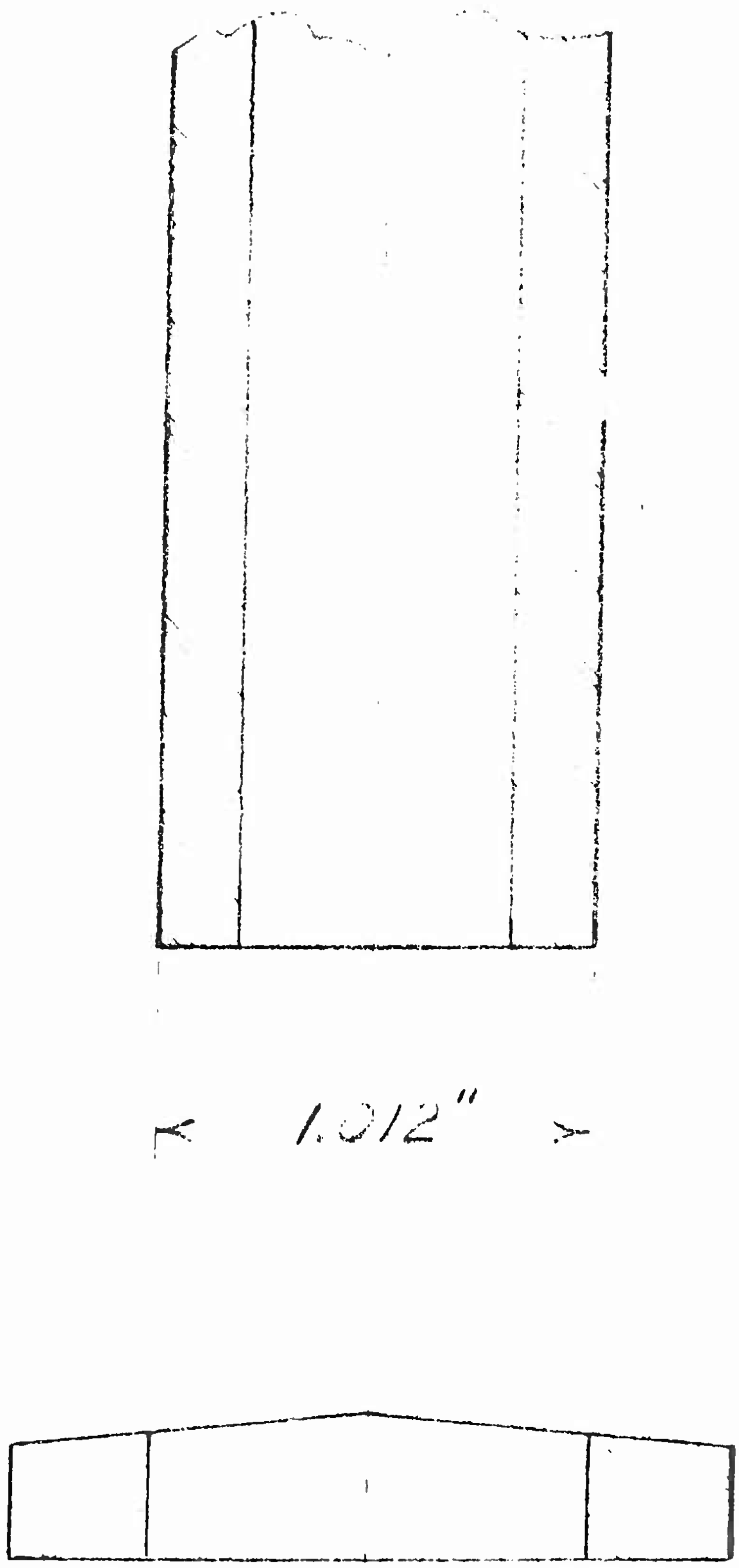
SKRL- [illegible]

exploratory nature. From the standpoint of gun design the desirability of a straight walled case had been recognized at the beginning of the project. The initial work was done on the mouth closure since the case shoulder insures positive chambering and it was reasonable to eliminate chambering problems from the case closure study at this stage. Furthermore, it was felt that the type of closure under consideration could be used equally well on the body of the case if this should prove desirable in practice.

A number of caliber .60 cases were cut off at the shoulder and counterbored according to drawing SKRL-12-1652-16 following page 30. These cases were loaded with 530 grains of a powder mixture consisting of 332 grains of 3996 lot 6432 powder and 198 grains of IMR 4350 powder. Closure was provided by disks blanked from a .125" thick cellulose nitrate sheet. (Refer to drawing SKRL-11-1 on the following page) The disks were seated on the counterbore and the mouth of the case was roll crimped over the disk. (Refer to drawing SKRL-11-452-2 following 11-1) The roll crimp was then ironed flat with an ironing punch. (Refer to drawing SKRL-11-3 following 11-452-2)

Five of these cartridges were fired for pressure, velocity and disk combustibility. The range floor was covered with paper and a large piece of muslin was hung 10 feet from the gun muzzle reaching from wall to wall and from the floor to a height of 10 feet. In this way the unburned disk fragments falling on the range floor or following the bullet down the range



SCALE 2X

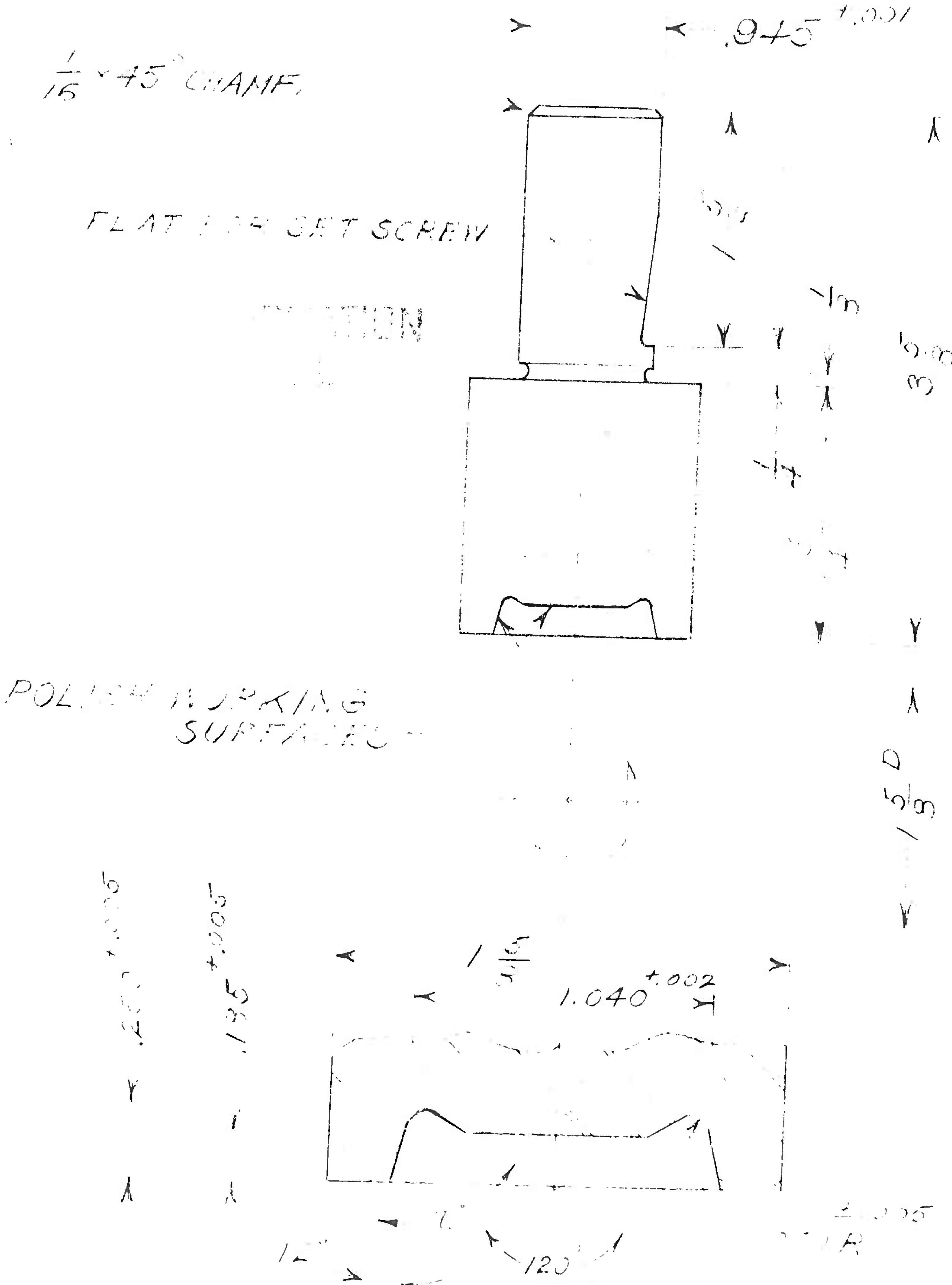
REMINGTON ARMS CO., INC., — BPT., CONN.
TECHNICAL DEPARTMENT

BLANKING PLATE 40.L(#2) [illegible]

UNCONVE[illegible] C[illegible]

DRAWN BY: Weymouth DATE: 12-8-52

SKRL- 11-1



HARDEN

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TECHNICAL DEPARTMENT

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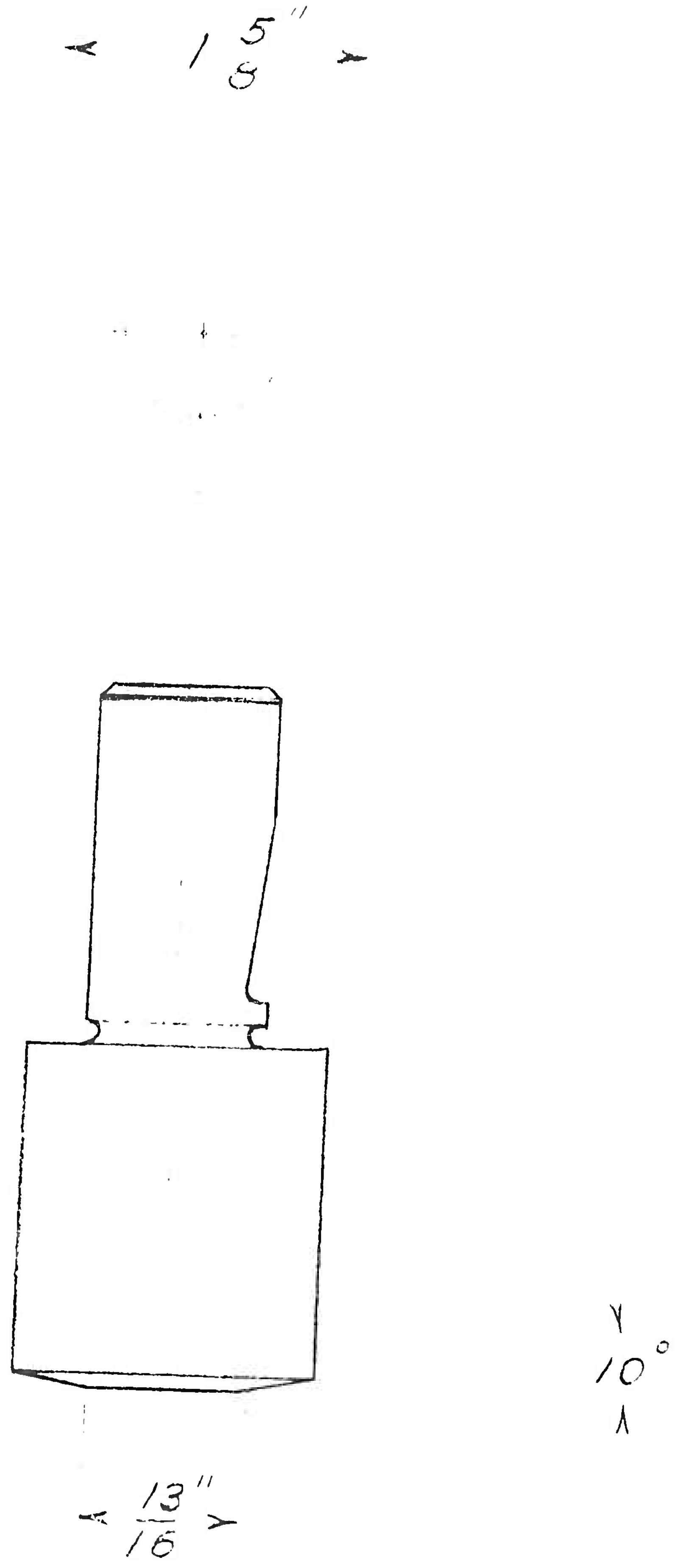
SKRL-



MAT'L - SPEC. 7
HARDEN Rc 62-64

REMINGTON ARMS CO., INC., — BPT., CONN. TECHNICAL DEPARTMENT
IRONING PUNCH (#2)
UNCONVENTIONAL CAL .60
DRAWN BY Weymouth DATE: 12-8-52
SKRL- 11-3

could be detected. Fragments of disk material collected gave evidence of incomplete combustion. The test was too small to be conclusive but indicated that a thinner sheet would be required for complete combustibility.

Additional tests were run using thinner closure disks. In these tests the special straight walled cases (drawing SKRL-12-1652-6 following page 30) were used. These tests were fired in the free bore gun. The cases were loaded with 332 grains of 4996 powder and 198 grains of 4350 powder. This load was chosen because it develops normal caliber .60 peak pressure in the free run barrel with a free run of 1.450". Closure of the cases was effected with Pyralin disks .088" thick.

The tests were conducted in the manner described above. After firing each round the range floor was swept to recover disk fragments stopped by the muslin screen. The average thickness of such fragments was found to be .069" with an extreme variation of .005". Since the original disk thickness was .088" this indicated that only about .019" is burned from the disk thickness in the gun. It likewise shows that low nitrogen Pyralin of this thickness does not have burning rate sufficiently high for this application.

Some high nitrogen content cellulose nitrate, type 666, was received from the Nixon Corporation. This material was in sheet form 1/16" thick. Combustibility tests were run using this material and the same loads and procedure described above for Pyralin. The average thickness of recovered disk fragments was .044". Hence only .063"-.044" or .019" was burned in the gun. The result was the same as in the case of the Pyralin.

The type 666 material employs camphor as a plasticizer. It is felt that this slows down the burning rate. It was not possible to obtain a faster burning cellulose nitrate sheet from the manufacturer.

60-40 Ballistite sheet was also tried. This had sufficient burning rate but lacked the requisite physical stiffness to provide a good closure. No more consideration, therefore, was given to this material.

Another closure material that was tested was Hercules JPN sheet. The base of this material is JPN propellant. In appearance it is black and opaque due to the addition of carbon black. This particular sample had a thickness of .063". Physically the material lacks the stiffness of Pyralin but is superior to ballistite in this regard. Combustibility tests were carried out on JPN in the manner described above. No closure fragments were recovered showing that the closure material was all burned in the gun. If the case finally adopted for use in this gun has less wall taper than the caliber .60, a wider shoulder can be employed as a seat for the closure disk. Under such circumstances the Hercules JPN material could possibly be used for closure.

Closure disks were also made by slicing regular single-base stick cannon propellant into disks .060" thick. This propellant was unperforated. It was originally machined to the proper O.D. No combustibility tests were run on this material since it did not offer any advantages over the Hercules JPN.

It was not as stiff and did not have as high a linear burning rate at atmospheric pressure.

Efforts were continued to obtain a satisfactory closure material. About twenty different samples of sheet propellant were received from Hercules Powder Company. Each sample represented a different propellant composition. On examination none proved satisfactory as case closure material.

B. Physical Strength of Closure

A fixture for testing the strength of the case closure was designed and built. A photograph of this fixture is shown in figure 19 on the following page. It consists essentially of a framework, a chamber block, an accelerating spring, and a fixed stop. A caliber .60 cartridge is inserted in the chamber block, B. The block is then pushed into the cap, C, and accelerated by means of the compression spring against the stop, S, when the spring is released by the trigger T.

The spring force was measured and found to be 112 pounds for full compression. The computed velocity of the chamber block in which the test cartridge is inserted was 26 feet per second. The actual striking velocity was measured with a Potter chronograph and found to be 26.7 feet per second.

Some of the special cases (see drawing SKRL-12-1652-6 following page 30) were loaded with 525 grains of 4996 powder and dummy primers. These cartridges were tested in the fixture. The fixture is supposed to simulate the treatment that a case receives on being chambered in an automatic weapon.

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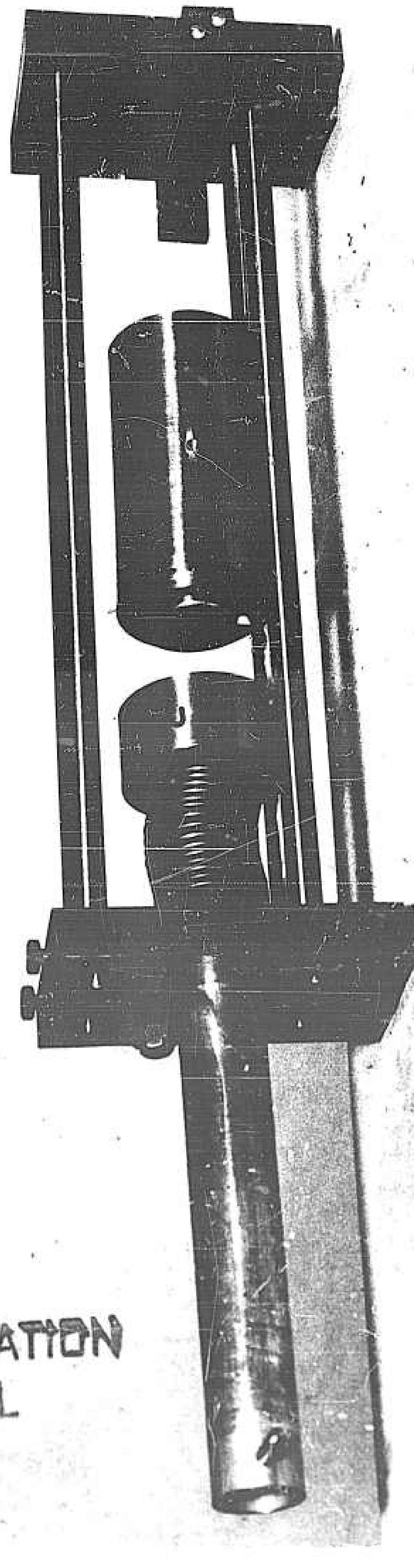

Fig. 19

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No visible injury to crimp or closure could be observed even on cartridges having the thinnest closure disks (.040" cellulose nitrate) after 5 repeated runs.

Similar cartridges employing .040" closure disks were dropped from a height of 10 feet onto concrete so as to strike asymetrically on the case mouth. Such treatment did not seriously injure the crimp or prevent chambering of the round.

These tests indicate that the closure had adequate physical strength for use in automatic weapons and to withstand the abuse of normal handling.

C. Conclusions

A closure material made from propellant must satisfy two requirements. It must have a thickness of at least .040" and a stiffness comparable to ordinary cellulose nitrate in order to provide sufficient mechanical strength. In addition the material must have a linear burning rate greater than conventional propellants in order that it may be consumed before reaching the muzzle.

From the powder maker's standpoint these requirements are to a degree antagonistic. Materials which enhance burning rate are in general good plasticizers. Stiffness can be increased by reducing residual solvents to a minimum. The propellant then becomes so brittle that it cannot be rolled.

It appears then that powder technology has nothing further to offer toward a solution of this problem. Two other possibilities could be investigated. One is to design a closure disk which under pressure would break into small pieces of larger burning area. This might be accomplished, for example, by perforating the disk, or by building it up in laminations, or even by pre-engraving it with segmental lines of cleavage.

A second possibility is to use an entirely different type of material. It is understood that studies have been made of a stiff plastic material impregnated with potassium perchlorate. Of special importance would be the sensitivity of this material to friction and impact. From this standpoint its practicability in this application seems doubtful.

A second possibility is nitrated cotton cloth. It is not known whether such material is available. Such material should have the required physical strength. Because of the form of this material the burning should be rapid provided the web in the interstices is burned through first thus leaving a large surface area for the flame to act upon.

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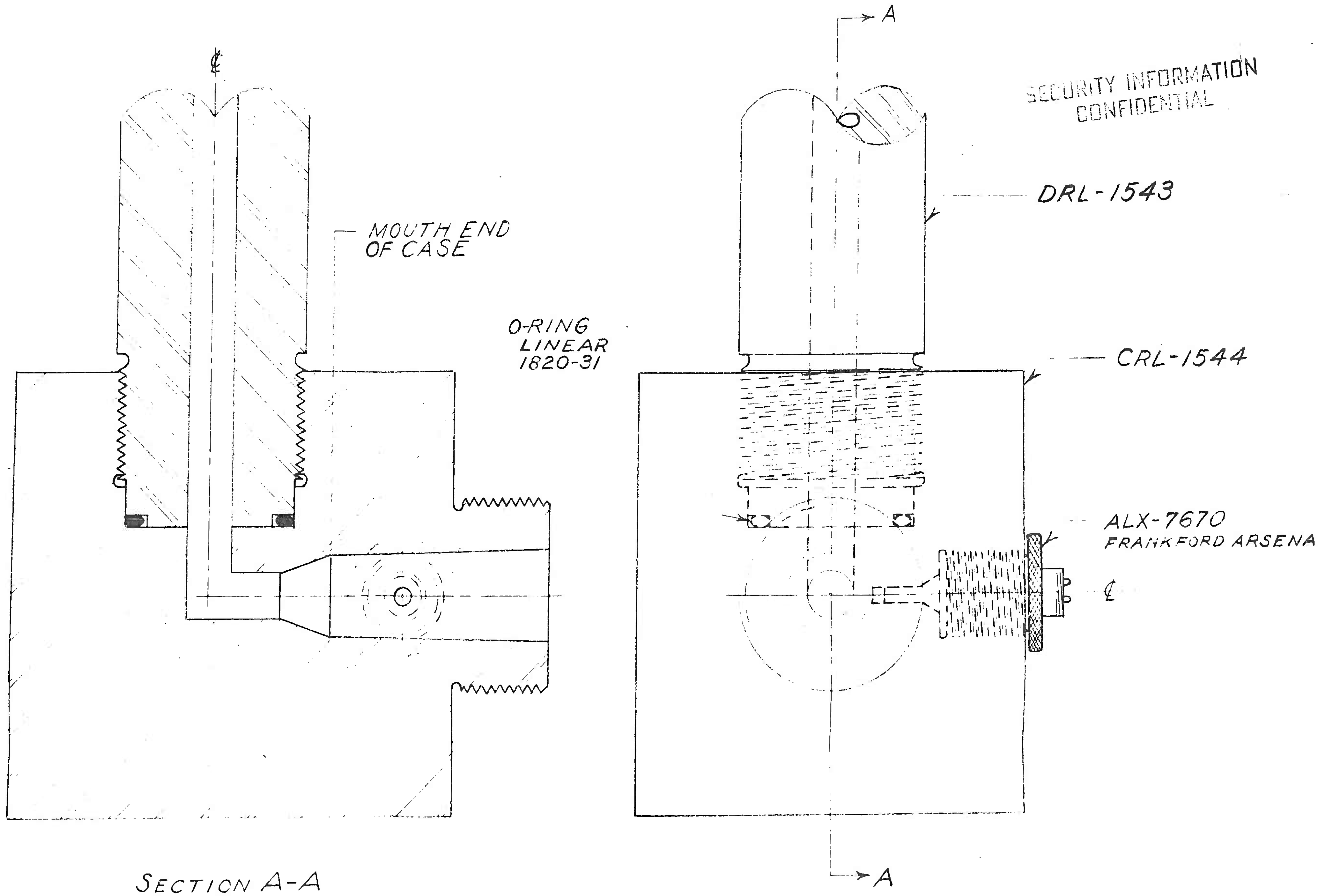
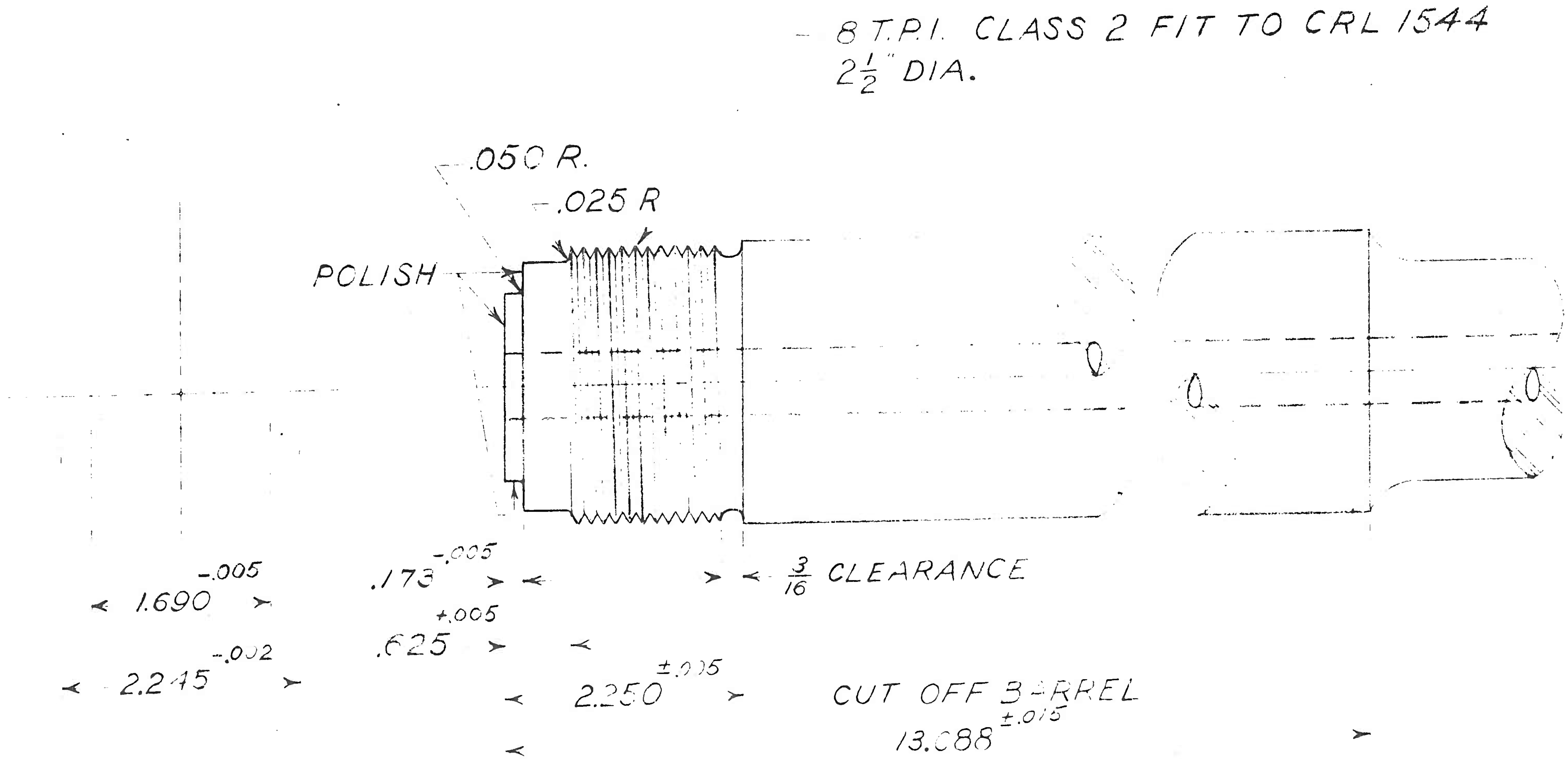


DEC 29 1953

SPECIFICATION NO.	DRAWING NO. CRL-1542	REMINGTON ARMS CO. INC. BRIDGEPORT WORKS
SUPERSEDES DWG	SCALE 1 TO 1	ORDER NO.
CONST. DWG	MAIN TITLE ASSEMBLY-TEST FIXTURE	
	SUB TITLE UNCONVENTIONAL CAL. .60	
DESIGN BY WEYMOUTH 8-27-52	TRACED BY	APPROVED
DRAWN BY	CHECKED BY	APPROVED

RECORD OF ALTERATIONS

ADDITIONAL USES



BREAK ALL CORNERS

MAT'L - CAL. .60 TEST BARREL. SEE ORD. DEPT DWG. D82566

1 REQUIRED

SPECIFICATION NO.		DRAWING NO. DRL-1543	REMINGTON ARMS CO. INC. BRIDGEPORT WORKS
SUPERSEDES DWG.		SCALE 1 TO 1	ORDER NO.
CONST. DWG.		MAIN TITLE REVISION TO BARREL	
		SUB TITLE UNCONVENTIONAL CAL. .60	
DESIGN BY WEYMOUTH	8-27-52	TRACED BY	APPROVED / APPROVED
DRAWN BY		CHECKED BY	APPROVED / APPROVED

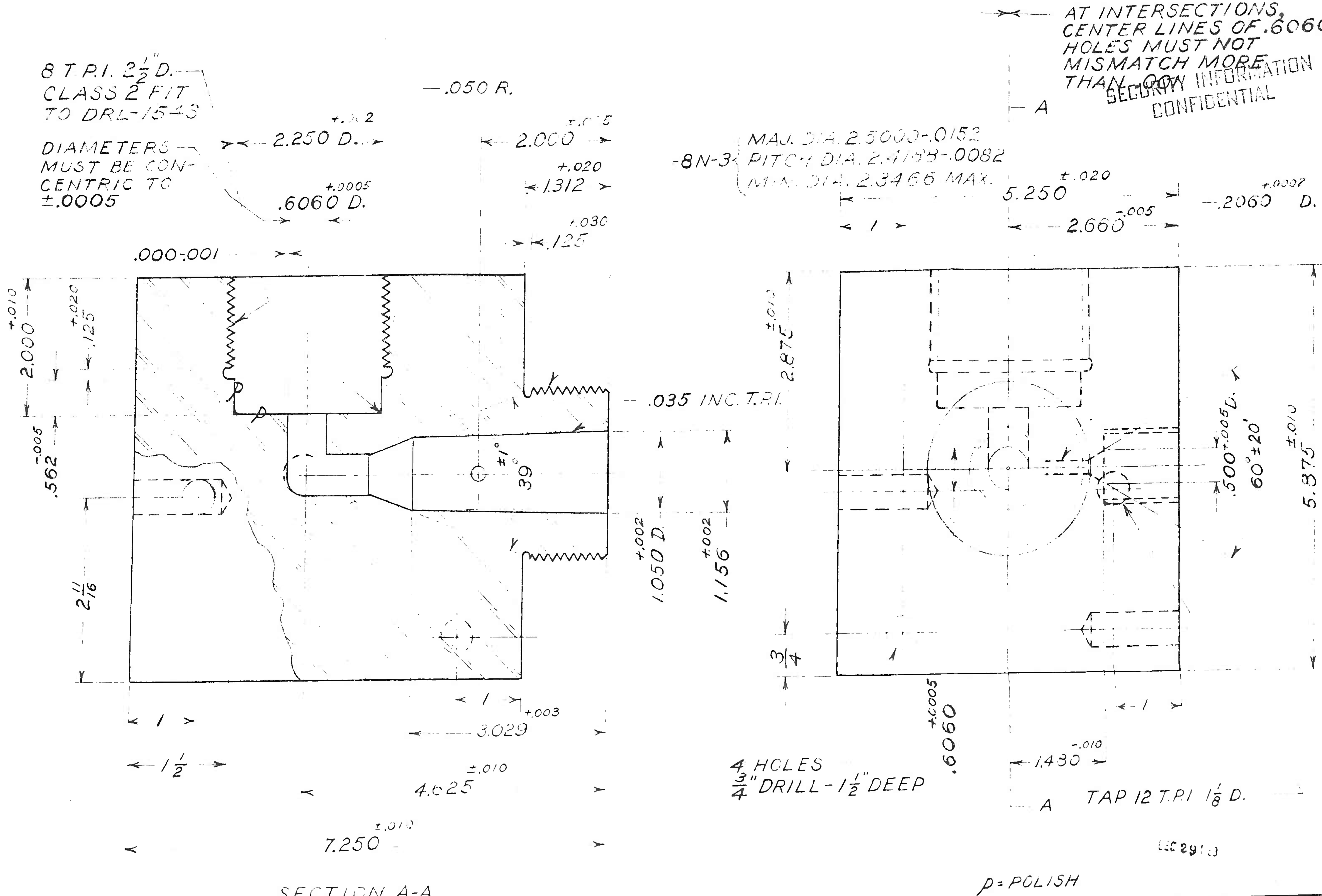
2-6-53 2.245 was 2.250

RECORD OF ALTERATIONS

ADDITIONAL USES

UNLESS OTHERWISE SPECIFIED ALL FRACTIONAL FINISH DIMENSIONS $^{+.01}_{-.01}$ ALL DECIMAL DIMENSIONS $^{+.001}_{-.001}$ DO NOT SCALE THIS DRAWING WORK TO FIGURES

Form RD-665



P = POLISH

MAT'L - CARPENTERS 5-317 OR EQUIV'T
OIL QUENCH AT 1500°F
DRAW AT 300°F

BREAK ALL CORNERS

1 REQUIRED

FRACTIONAL TOLERANCE = ±1/64

3/4" DRILL WAS 1/2 10-20-52
+.002 TOL. WAS +.0005 2-9-53

UNLESS OTHERWISE SPECIFIED ALL FRACTIONAL FINISH DIMENSIONS ±.01 ALL DECIMAL DIMENSIONS ±.001 DO NOT SCALE THIS DRAWING WORK TO FIGURES

ADDITIONAL USES

SPECIFICATION NO.	DRAWING NO. CRL-1544	REMINGTON ARMS CO. INC. BRIDGEPORT WORKS
SUPERSEDES DWG.		SCALE 1 TO 1 / ORDER NO.
CONST. DWG.	MAIN TITLE BLOCK	
	SUB TITLE UNCONVENTIONAL CAL. .60	
DRAWN BY WEYMOUTH 8-27-52	TRACED BY / CHECKED BY	APPROVED / APPROVED